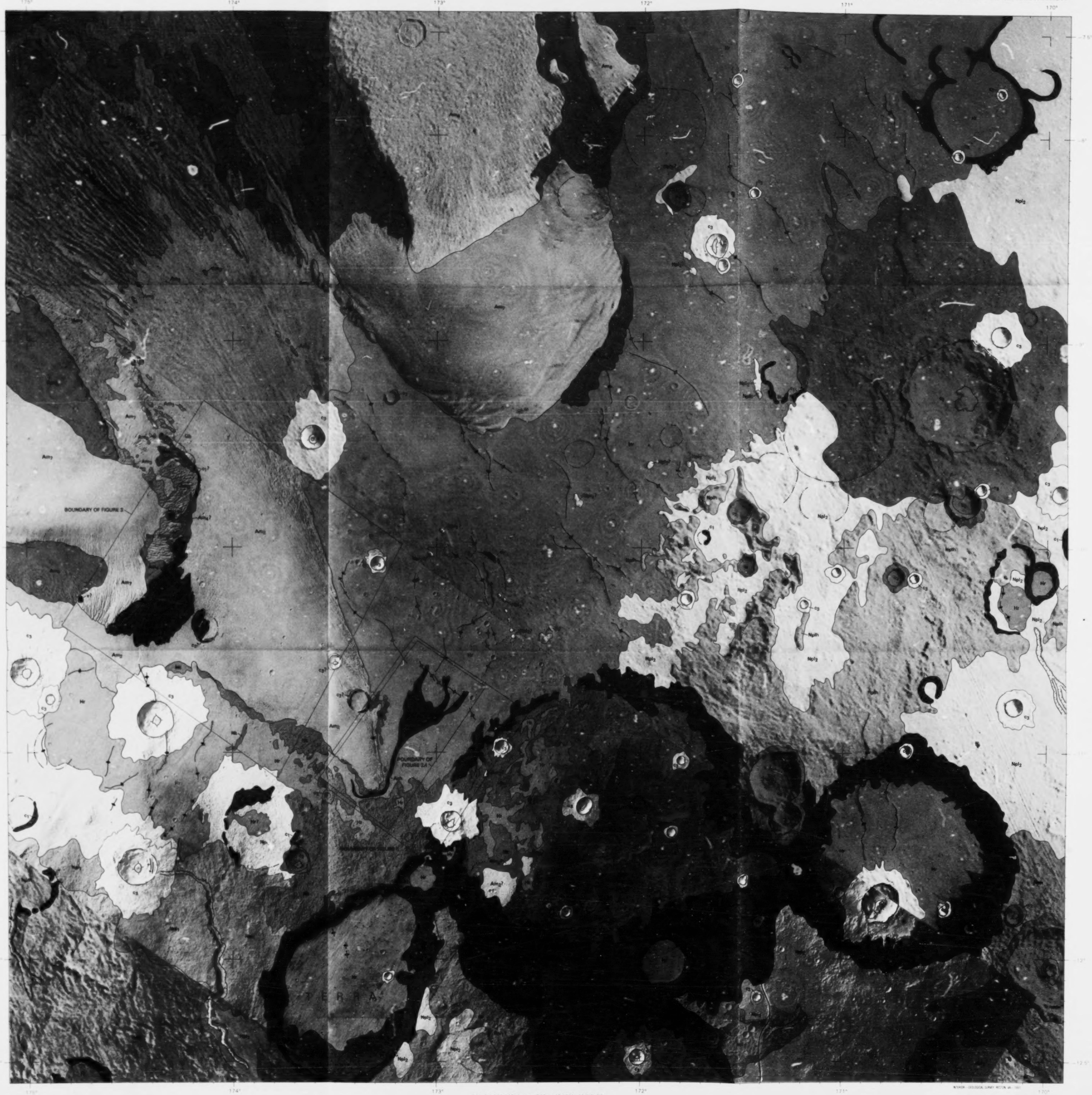
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION



Base compilation by U.S. Geological Survey

INTERIOR—GEOLOGICAL SURVEY, RESTON, VA—1991

Prepared on behalf of the Planetary Geology Program, Solar System Exploration Division, Office of Space Science, National Aeronautics and Space Administration, under contract W-15,814

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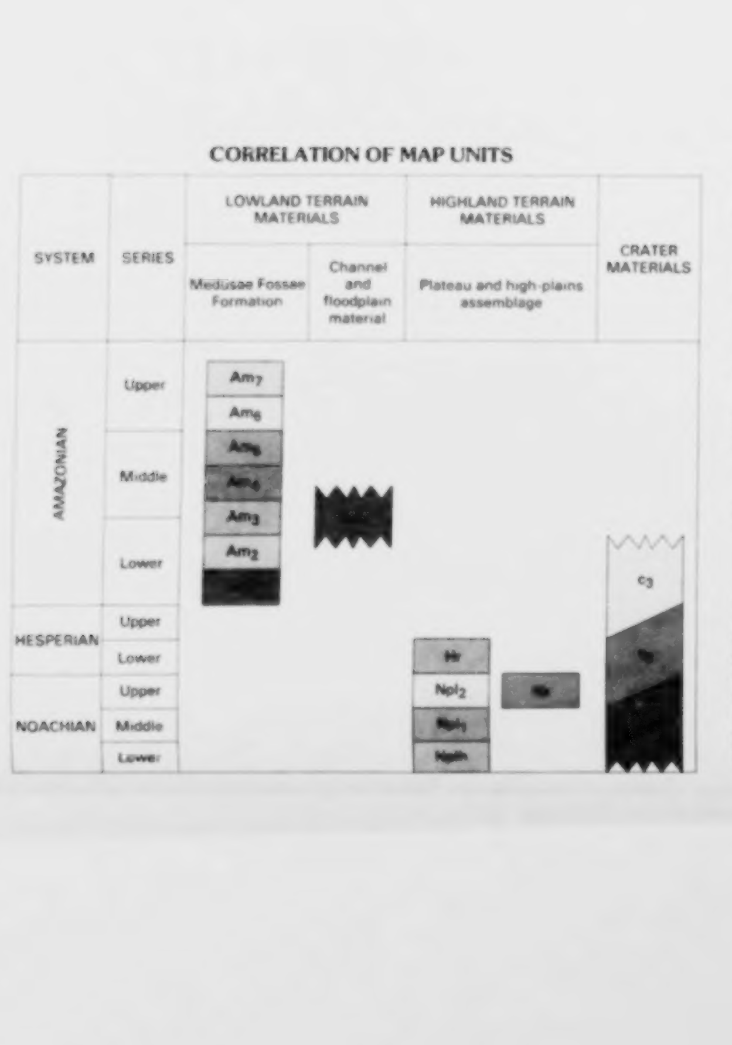
CORRELATION OF MAP UNITS



HIGHLAND TERRAIN MATERIALS

Plateau and high-plains assemblage

Hr **Ridged plains material**—Occurs on central valley floor and floors of c_1 and c_2 craters; smooth, relatively flat surface with curvilinear, northwest-trending ridges; moderately cratered. *Interpretation:* Lava flows probably erupted from fissure vents

Npl2 **Subdued cratered material**—Forms plains marked by subdued and partly buried old crater rims. *Interpretation:* Thin mantle of lava flows and eolian deposits that partly bury underlying rocks

Nk **Knobby material**—Forms knobs and small rounded to partly streamlined hills commonly in linear arrays trending northwest; less hummocky and of lower albedo on floor of large highland crater centered at lat 11.5° S., long 172°. *Interpretation:* Volcanic material highly modified in central valley by fluvioglacial processes

Npl1 **Cratered material**—Rough, irregular surface with buried and partly buried crater rims; transected in places by small valleys with medial channels. *Interpretation:* Mixture of lava flows, impact breccias, crater-rim material, and minor eolian and fluvial deposits

Nplh **Hilly material**—Similar to cratered material but contains more peaks and large ridges; buried crater outlines common. *Interpretation:* Same as cratered material but tectonic deformation greater

CRATER MATERIALS

[Impact craters are assigned relative ages on basis of recognizable morphologic appearance and superposition relations. Craters of c_3 age have sharp, fresh-appearing rim crests; most ejecta blankets extend about one crater diameter beyond rim crest. With increasing age, craters become progressively more degraded and subdued in appearance, and their ejecta deposits are discernible only relatively close to rim crest. On Correlation of Map Units, overlaps are indicated between crater-age classes and time-stratigraphic boundaries. Craters with rim crests <3 km in diameter are not mapped]

c3 **Material of craters having sharp rim crests**—Fresh-appearing craters having continuous rims and broad ejecta blankets; smaller craters bowl shaped; central peaks common; crater floors rough to smooth.

INTRODUCTION

The geologic map shows an area within the Memnonia region that has been proposed as a candidate landing site for a Mars sample-return mission. Site-selection priorities are constrained by the terrain roughness, which may affect the descent of the landing craft and the mobility of the sampling vehicle. Evaluation of small-scale topographic features (<50 m of relief) can be made only in a very general way from available imagery. For this reason the candidate site in this map area is provisionally recommended primarily on the basis of its high scientific value; however, no adverse surface conditions are discernible in the site area at the resolution (~50 m/picture element) of Viking images.

Geologic studies of the site area made from computer-enhanced, high-resolution images show that rocks having a wide range of ages and inferred compositions are accessible to a roving vehicle. Geologic and other information obtained from samples of these rocks would fulfill many of the primary criteria that are necessary to advance our understanding of the evolutionary history of Mars (Scott and Tanaka, 1987; Scott, 1988). In addition, a recent fluvial episode is evidenced by a small channel in the site area that has incised materials emplaced during the Amazonian Period. The channel may have been carved by water mobilized from ice in the subjacent regolith by overriding ashflows (Scott and Chapman, 1989). The presence of this young channel has important implications for the possible occurrence and distribution of shallow ground water in the equatorial regions of Mars, as well as for Mars' climatic history.

Geologic mapping was compiled on a Viking 1:500,000-scale photomosaic base, and photoclinometric profiles were obtained over selected areas to investigate the shape of the channel and its bedforms. Map units generally correspond to those shown on the geologic map of the western equatorial region of Mars (Scott and Tanaka, 1986). In places, however, interpretations and contacts have been revised to reflect more detailed information visible on high-resolution Viking images that were enhanced by spatial filtering (Condit and Chavez, 1979).

GEOLOGIC SETTING

The map area is in the Memnonia northwest subquadrangle (MC-16NW; U.S.

surfaces on the old material. The subdued cratered unit (unit Npl_2) has such surfaces: crater rims, ridges, and hills are recognizable beneath the mantle, but the coarse texture of intercrater areas is obscured.

Material having a knobby and hilly appearance (unit Nk) is assigned a Late Noachian age, but its assignment is provisional because its stratigraphic position is uncertain. The unit overlies rocks as young as Late Noachian (c_1 crater material and the subdued cratered unit), but it appears to be embayed by lava flows of the Lower Hesperian ridged plains material (unit Hr). However, the knobby unit also appears to be transitional in places with the basal part of member 2 (unit Am_2) of the Medusae Fossae Formation of Amazonian age. This ambiguity cannot be resolved by available Viking imagery. At the map scale, the knobby material appears coarse to fine textured and commonly lineated (fig. 2A); individual knobs and hills are about 100 to 500 m across. Where the unit occurs within the large (100-km-diameter), unnamed crater centered at lat 11.5° S., long 172.5°, it appears grossly dissected with a surface covered by small, evenly spaced hills; a lobe of the material extends into a calderalike depression on the crater floor. Around the southeast side of the depression, the knobs and small hills that elsewhere characterize the unit grade into relatively smooth terrain marked by a catena (a chain of pit craters), minor valleys, and tubelike ridges radiating from the rim of the calderalike landform. Although the knobby material in its various morphological aspects is mapped as a single unit, it may consist of several materials having different origins and ages. A volcanic origin and Noachian age are suggested by its lobate, flowlike margins, what appear to be collapsed lava tubes, and its occurrence in the large, ancient impact crater. The seemingly gradational relation of knobby material with a member of the Medusae Fossae Formation seems to indicate an Amazonian age and a possible pyroclastic origin. In other places, particularly in the valley around a small outflow channel (whose fill is mapped as unit Ach), the smaller knobs and hills occur both in linear arrays trending northwest and in clusters; the clusters resemble the beaded eskers and drumlin tracts of a glaciated landscape. These features, as well as the young outflow channel, suggest that postdepositional fluvioglacial processes might have been active during the Amazonian in this area.

HESPERIAN SYSTEM

1987). Within the map area there is no surety that noncontiguous outcrops represent the same deposit even though their morphology and homotaxial relations may be similar.

The prominent ridges (fig. 3) and intervening grooves carved on most members of the formation have been attributed in places to prevailing wind or paleowind erosion (Zimbelman and Wells, 1987; Schultz and Lutz, 1988). Scott and Tanaka (1982) noted that erosional patterns on one member of the formation follow the present dominant wind direction but that other members exhibit lineament sets intersecting at acute angles.

The orientation of grooves and ridges on members of the Medusae Fossae Formation and the present prevailing wind direction (indicated by bright streaks in the lee of surface obstacles) are shown in figure 4. Only major grooves and ridges on the oldest member (unit Am_1) are generally aligned with the wind direction; on all other members they are normal or nearly normal to it. Here, as well as elsewhere on the Medusae Fossae Formation (Scott and Tanaka, 1982), groove and ridge patterns commonly occur in sets that have acute junction angles. For this reason we interpret grooves and ridges as wind-erosion features scoured along complementary joint sets in formation members rather than as representations of variations in paleowind directions alone. Wrinkle ridges in ridged plains material largely follow the northwest-trending and best defined joint sets in members 2, 3, and 4 (fig. 4). This observation does not necessarily imply that the stress fields responsible for formation of both types of features were either similar or contemporaneous. (A fuller discussion is given in Structure.)

Channel and flood-plain material (unit Ach) is considered Early to Middle Amazonian in age because its enclosing channel cuts member 2 of the Medusae Fossae Formation (fig. 2A). Conspicuous erosional/depositional bedforms occur in its broad discharge area, which is large relative to the short, straight "upstream" reach of the channel (northeast of the tip of member 2).

ORIGIN OF AMAZONIAN CHANNEL

The morphology and geologic setting of the channel provide some constraints on its origin. Morphologically, it is a miniature analog of other Martian outflow channels. However, the head of the channel is not associated with collapsed or chaotic terrain, as at

bedforms were investigated by photoclinometric profiles that were obtained over selected areas.)

This hypothesis cannot be fully developed because emplacement temperatures, cooling histories, original thicknesses of the ash flows, and depth to ground ice are unknown. Some of these parameters can be estimated in terrestrial ash flows of known composition and thickness by their degrees of welding and crystallization; plausible assumptions might be made for these and other factors pertaining to the Amazonian channel, but they are beyond the scope of this study.

Other possible origins for the channel involve (1) water that may have been entrained as a volatile component of ash flows, (2) subterranean springs that may have existed beneath the Medusae Fossae Formation, (3) water that was discharged into the valley from large canyons in the bordering highlands, and (4) water that was released from paleopolar deposits (Medusae Fossae Formation) to form channels during the warming period following the hypothetical shift of the poles from the equatorial region to their present position (Schultz and Lutz, 1988).

Hypotheses other than those noted above can probably be conceived to explain the origin and processes responsible for the development of this young channel. However, the primary factors in resolving this important problem are the origin and composition of the Medusae Fossae Formation, which can be determined only from returned samples.

STRUCTURE

The physiographic boundary between the highland and lowland provinces is obscured in places where large accumulations of the young Medusae Fossae Formation overlap onto ancient highland terrain (fig. 1). The origin of this crustal dichotomy is unknown, but processes that have been hypothesized include mantle convection associated with core formation (Wise and others, 1979), a giant impact that formed a huge basin in the north polar region (Wilhelms and Squyres, 1984), and extensive southward erosional retreat of the highland plateau (Scott, 1978; Hiller, 1979). Whatever the origin of the dichotomy, the boundary clearly separates relatively young, uncratered materials of the lowlands from the highly cratered, ancient, highland rock assemblages.

Within the map area, the valley between the Medusae Fossae Formation in the lowlands and the adjacent highlands may be synclinal, possibly formed by downwarping during the Amazonian Period. Some evidence for this correspondence between topography and structure is suggested by the configuration of the valley fill (ridged plains material); the surface of this material, presumably deposited as relatively level lava flows, is now gently inclined in places toward the central part of the valley. Some members of the Medusae Fossae Formation, particularly member 6, also appear to dip and thin valleyward, further suggesting, along with grooves developed from joint sets (fig. 3), that tectonic activity occurred during the Amazonian.

With the exception of a 65-km-long, fresh-appearing, normal fault centered near lat 12.3° S., long 171.4°, little diastrophism in the highlands can be recognized in the map area.

Northwest-trending scarps form sublinear contacts locally at the base of members 2 and 4 of the Medusae Fossae Formation. These scarps may be related to normal fault displacements that have been subsequently modified by erosion and joint-block separation. Prominent wrinkle ridges on Hesperian ridged plains material are also oriented northwest, suggesting a causal relation between these two structural types as well as among the major grooves interpreted to have formed from joint sets (fig. 4). However, the faults, wrinkle ridges, and joints were unlikely to have formed concurrently during the Amazonian Period by similar stress fields. The existence of the ridges in the Hesperian Period is indicated in several places where they are overlapped by the Medusae Fossae Formation. Moreover, stresses producing normal faults and joints are extensional, whereas ridges, like folds, may largely be formed by compression (Howard and Muehlberger, 1973; Plescia and Golombek, 1986; Watters and Maxwell, 1986). Interpretations as to the origins of wrinkle ridges differ, however, and their occurrence in some areas has been attributed to lava intrusions and squeeze-ups along extension fractures and faults (Colton and others, 1972; Hodges, 1973; Scott, 1973; Young and others, 1973). Wrinkle ridges are also common on the Moon and Mercury and, although their origin remains obscure, they appear to have formed in conjunction with large deposits of volcanic material.

GEOLOGIC HISTORY

Following the accretion and impact cratering of the Martian crust during the high bombardment flux of the Early Noachian Epoch, endogenic or exogenic processes produced the Martian crustal dichotomy expressed by the highland and lowland regions. That the formation of their boundary predates the Hesperian Period is shown by overlaps of Lower Hesperian ridged plains material across the boundary both within and outside the map area. Resurfacing of the lowland plains occurred from the Early Hesperian through the Late Amazonian, largely by lava flows from many sources, including the Olympus-Tharsis volcanic province (Scott and Tanaka, 1980; Scott, 1982). An episode of local volcanism probably also occurred during the Noachian and Hesperian, producing the large, calderalike feature centered at lat 11.5° S., long 172° and possible associated lava flows.

Voluminous, areally extensive (2.2×10^6 km^2) ignimbrite deposits were postulated by Scott and Tanaka (1982) to have erupted in the Amazonian Period in an irregular east-west zone along the highland-lowland boundary. These deposits, mapped as the Medusae Fossae Formation, are represented in the map area by seven members. (The formation as a whole extends between long 127° and 221°, well beyond the boundaries shown in figure 1; Scott and Tanaka, 1982, 1986; Greeley and Guest, 1987.) Following the deposition of member 2, water mobilized from ground ice accumulated behind a tongue-shaped barrier formed by the southern tip of this member; subsequent breaching of this ash-flow dam produced an outflow of water that carved a narrow channel containing distributary landforms. The formation of this channel is the youngest recognizable event in the map area and one of the youngest on Mars.

A CANDIDATE LANDING SITE

ROVER TRAVERSES AND SAMPLE STATIONS

Eight primary objectives and six secondary objectives, or targets of opportunity, are located within 15 km of the landing site shown in figure 5; this site is thought to be the most favorable of several that could be selected in the map area. Traverse routes to the sample stations are provisionally laid out from the landing site, where contingency samples would be obtained; the routes appear to be relatively smooth and free of obstacles at image resolution (~50 m/pixel). However, much higher resolution images, possibly obtained from a Mars Observer or other missions, are considered necessary for the final selection of an optimum landing site and of rover traverses to the stations recommended for sampling.

The primary sample stations are numbered in table 1; targets of opportunity that might be sampled en route are indicated by letters. The landing and ascent sites are assumed to be the same or close together.

Like the candidate landing site in the Memnonia area, the other sites in the planned science study areas (fig. 6) maximize the probability of selecting samples that will answer the widest diversity of fundamental questions within reasonable mission constraints.

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Table 1. *Materials to be sampled on proposed landing-site traverses at primary sample stations (numbers) and secondary targets of opportunity (letters). Landing site (LS) and traverses shown in figure 5*

	Estimated minimum traverse distance	Sample description and geologic

Figure 1. Index
Medusae F
Amazonian
and Amazo
indicated by
(1986)

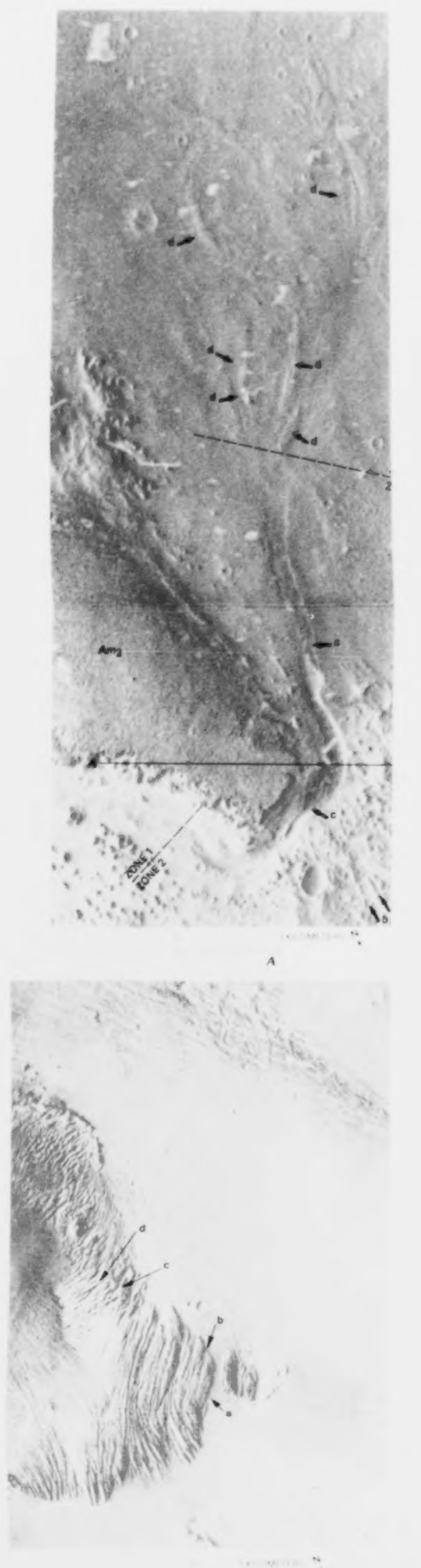

Figure 3. Ridges (yardangs) following joint sets in Medusae Fossae F
and b in member 1; ridges at c and d in member 3. Image center
174°.

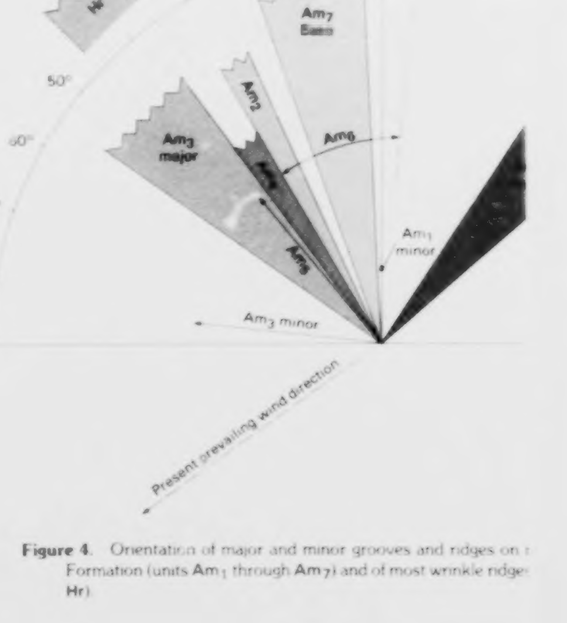

Figure 4. Orientation of major and minor grooves and ridges on
Formation (units Am_1 through Am_7) and of most wrinkle ridge
Hr).

ATLAS OF MARS
1:500,000 GEOLOGIC SERIES
MEMNONIA REGION
M 500K -10/172 G, 1991
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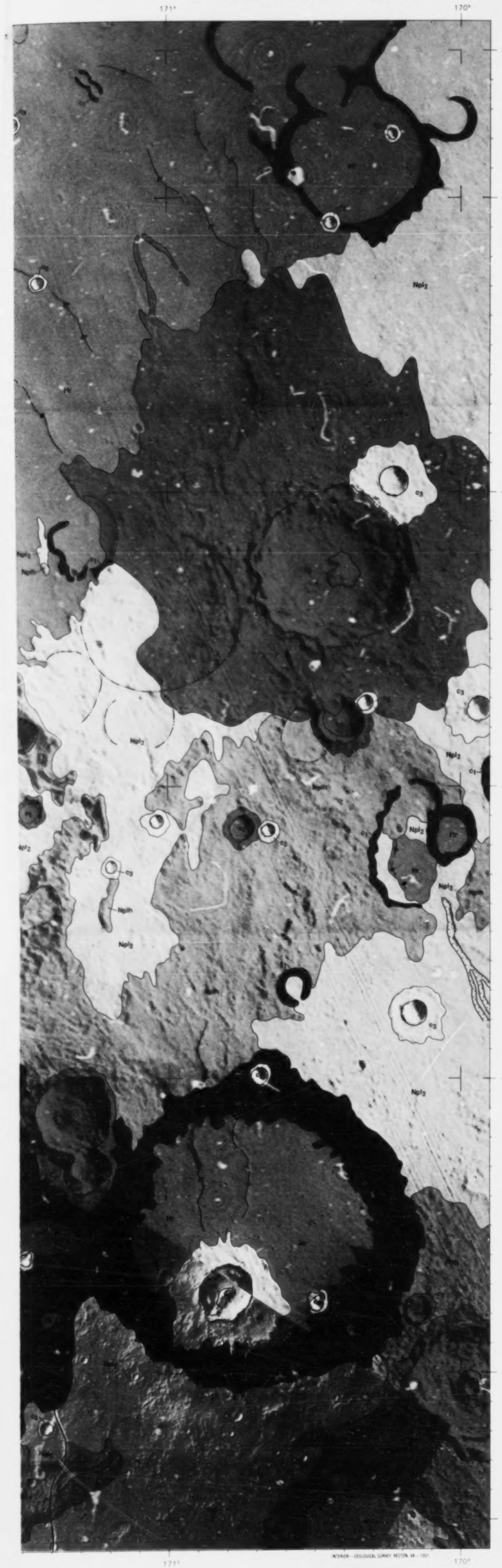

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Table 1. *Materials to be sampled on proposed landing-site traverses at primary sample stations (numbers) and secondary targets of opportunity (letters). Landing site (LS) and traverses shown in figure 5.*

	Estimated minimum traverse distance	Sample description and geologic

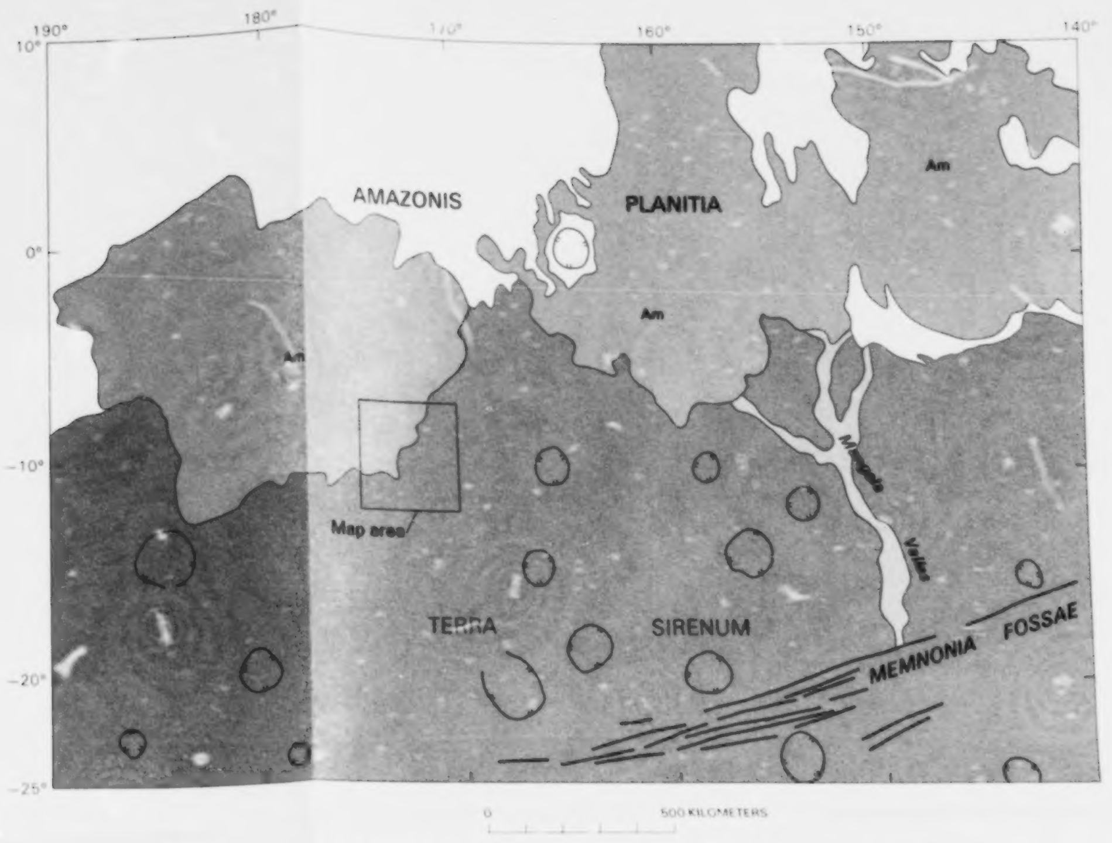


Figure 1. Index map showing location of map area in relation to major geologic features in this region of Mars. Medusae Fossae Formation (unit **Am**) has seven members in map area ranging from Early to Late Amazonian in age; formation lies across boundary between Noachian cratered highlands of Terra Sirenum and Amazonian relatively smooth lowlands of Amazonis Planitia. Large (>100-km-diameter) craters indicated by circular outlines, major faults and grabens by straight lines. Modified from Scott and Tanaka (1986).

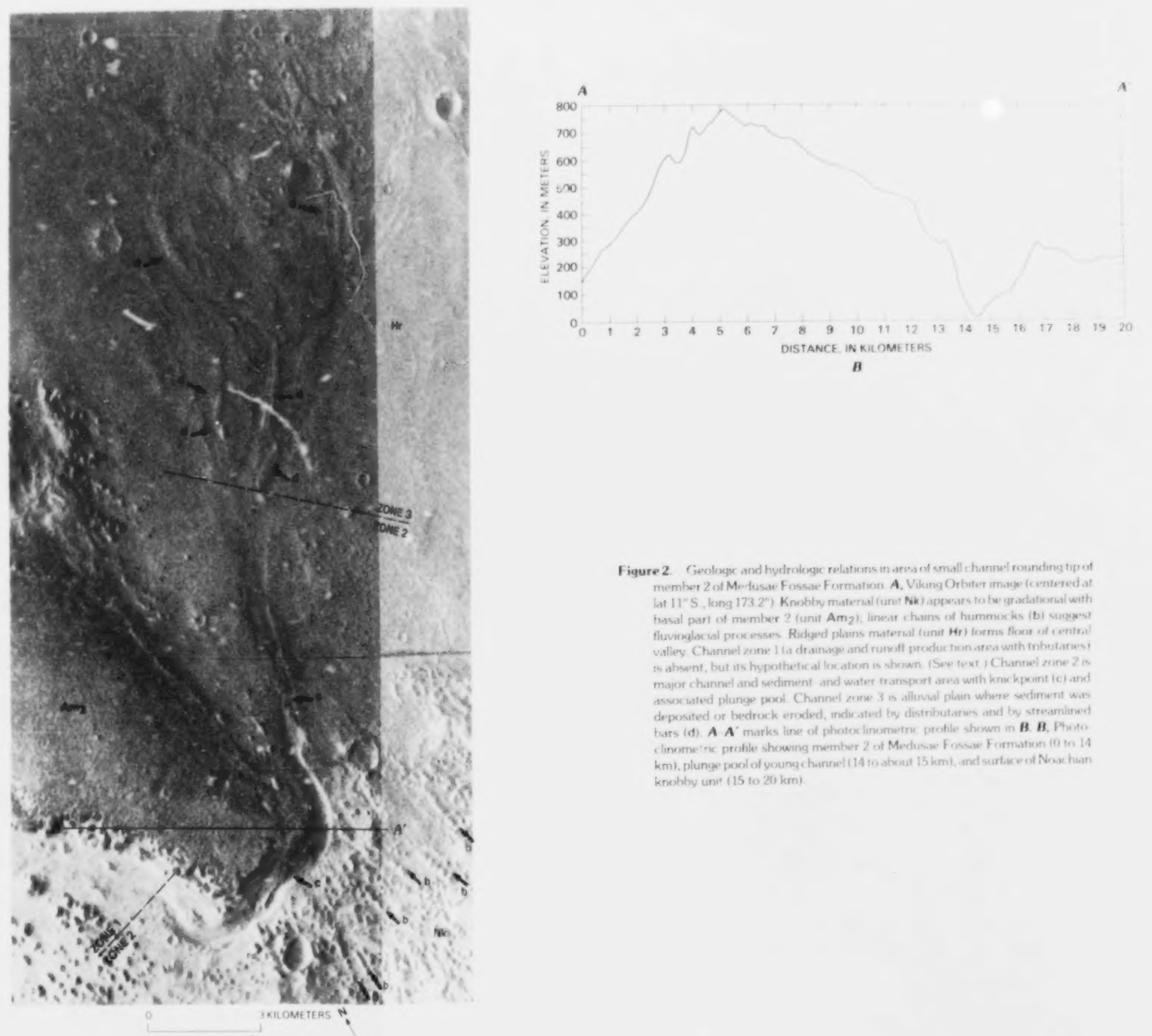


Figure 2. Geologic and hydrologic relations in area of small channel rounding tip of member 2 of Medusae Fossae Formation. **A**, Viking Orbiter image (centered at lat 11° S., long 173.2°). Knobby material (unit **Nk**) appears to be gradational with basal part of member 2 (unit **Am₂**); linear chains of hummocks (**b**) suggest fluvioglacial processes. Ridged plains material (unit **Hr**) forms floor of central valley. Channel zone 1 (a drainage and runoff production area with tributaries) is absent, but its hypothetical location is shown. (See text.) Channel zone 2 is major channel and sediment- and water-transport area with knickpoint (c) and associated plunge pool. Channel zone 3 is alluvial plain where sediment was deposited or bedrock eroded, indicated by distributaries and by streamlined bars (d). ***A–A′*** marks line of photoclinometric profile shown in ***B***. ***B***, Photoclinometric profile showing member 2 of Medusae Fossae Formation (0 to 14 km), plunge pool of young channel (14 to about 15 km), and surface of Noachian knobby unit (15 to 20 km).

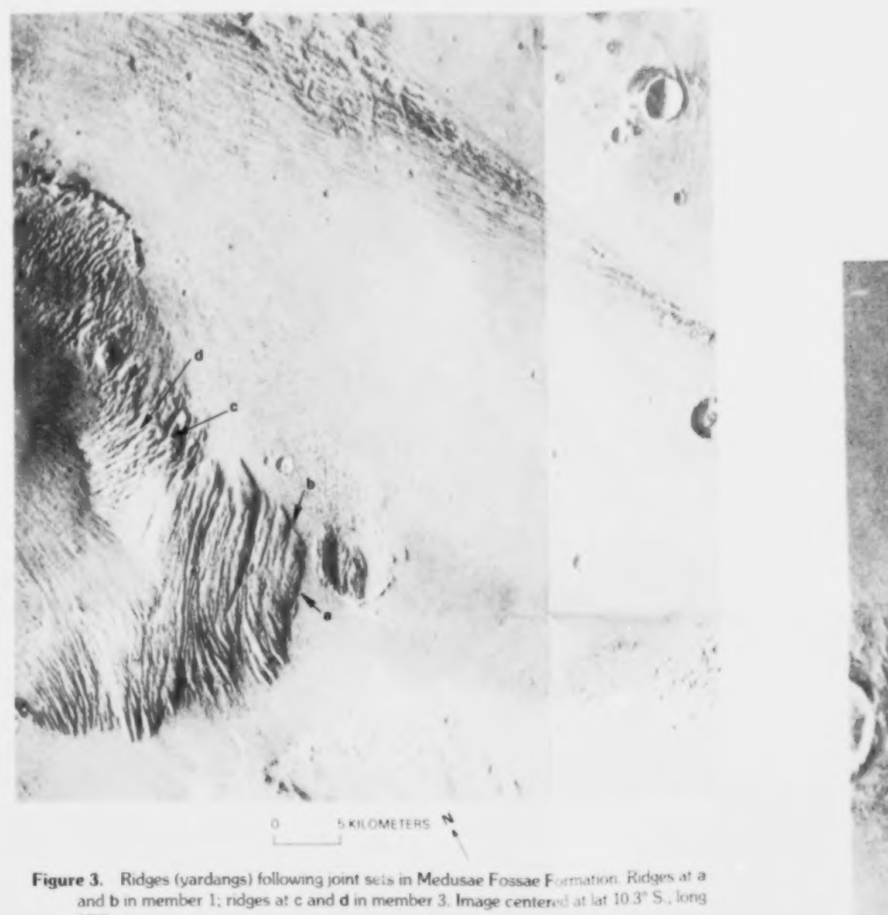


Figure 3. Ridges (yardangs) following joint sets in Medusae Fossae Formation. Ridges at a and b in member 1; ridges at c and d in member 3. Image centered at lat 10.3° S., long 174°.

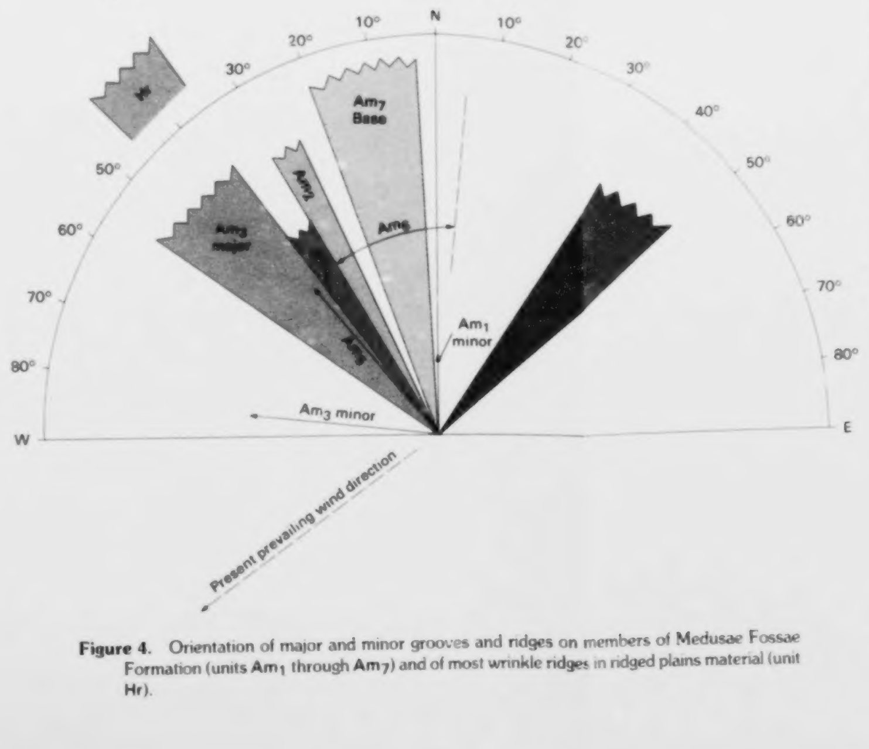


Figure 4. Orientation of major and minor grooves and ridges on members of Medusae Fossae Formation (units **Am₁** through **Am₇**) and of most wrinkle ridges in ridged plains material (unit **Hr**).

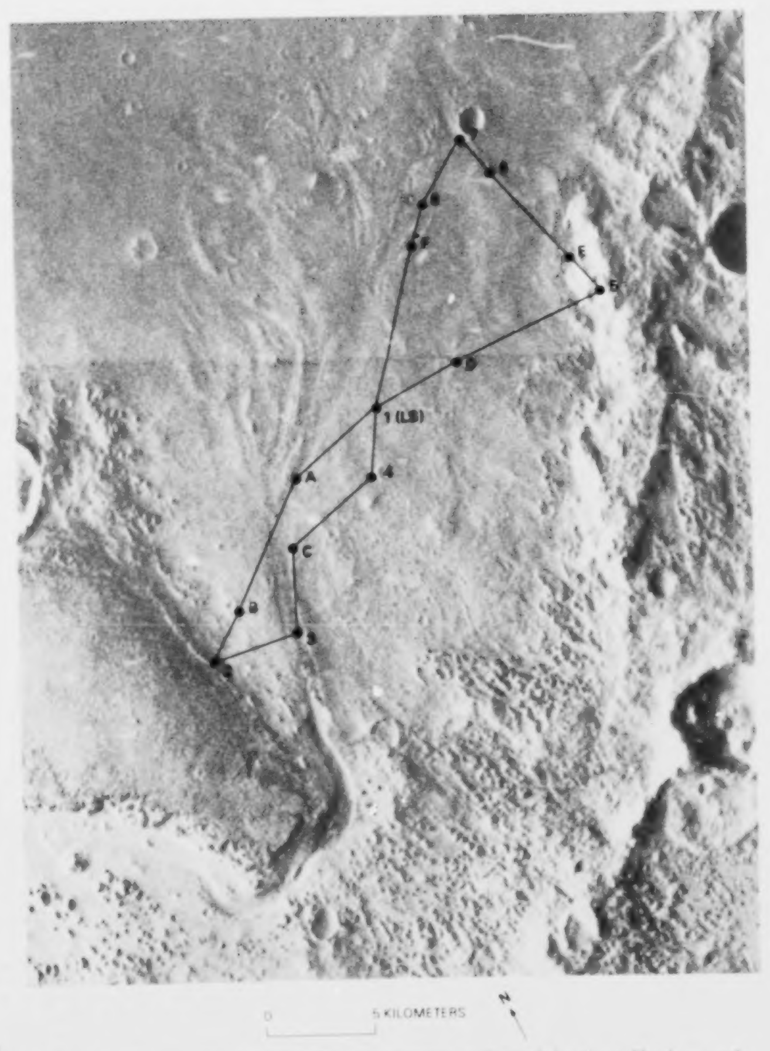


Figure 5. Proposed landing site (LS), rover traverses, and sample locations. Numbers mark primary sample locations; letters mark secondary target-of-opportunity sites. Samples and locations described in table 1.

old material. The subdued cratered unit (unit **Npl₂**) has such
rms, ridges, and hills are recognizable beneath the mantle, but the
ntercrater areas is obscured.
g a knobby and hilly appearance (unit **Nk**) is assigned a Late Noachian
nent is provisional because its stratigraphic position is uncertain. The
s as young as Late Noachian (c₁ crater material and the subdued
t appears to be embayed by lava flows of the Lower Hesperian ridged
it **Hr**). However, the knobby unit also appears to be transitional in
al part of member 2 (unit **Am₂**) of the Medusae Fossae Formation of
his ambiguity cannot be resolved by available Viking imagery. At the
bby material appears coarse to fine textured and commonly lineated
knobs and hills are about 100 to 500 m across. Where the unit occurs
0-km-diameter), unnamed crater centered at lat 11.5° S., long 172.5°, it
ssected with a surface covered by small, evenly spaced hills; a lobe of
ds into a calderalike depression on the crater floor. Around the
he depression, the knobs and small hills that elsewhere characterize
relatively smooth terrain marked by a catena (a chain of pit craters),
tubelike ridges radiating from the rim of the calderalike landform.
by material in its various morphological aspects is mapped as a single
of several materials having different origins and ages. A volcanic origin
are suggested by its lobate, flowlike margins, what appear to be
es, and its occurrence in the large, ancient impact crater. The
nal relation of knobby material with a member of the Medusae Fossae
o indicate an Amazonian age and a possible pyroclastic origin. In other
in the valley around a small outflow channel (whose fill is mapped as
ler knobs and hills occur both in linear arrays trending northwest and
aters resemble the beaded eskers and drumlin tracts of a glaciated
features, as well as the young outflow channel, suggest that

1987). Within the map area there is no surety that noncontiguous outcrops represent the same deposit even though their morphology and homotaxial relations may be similar.

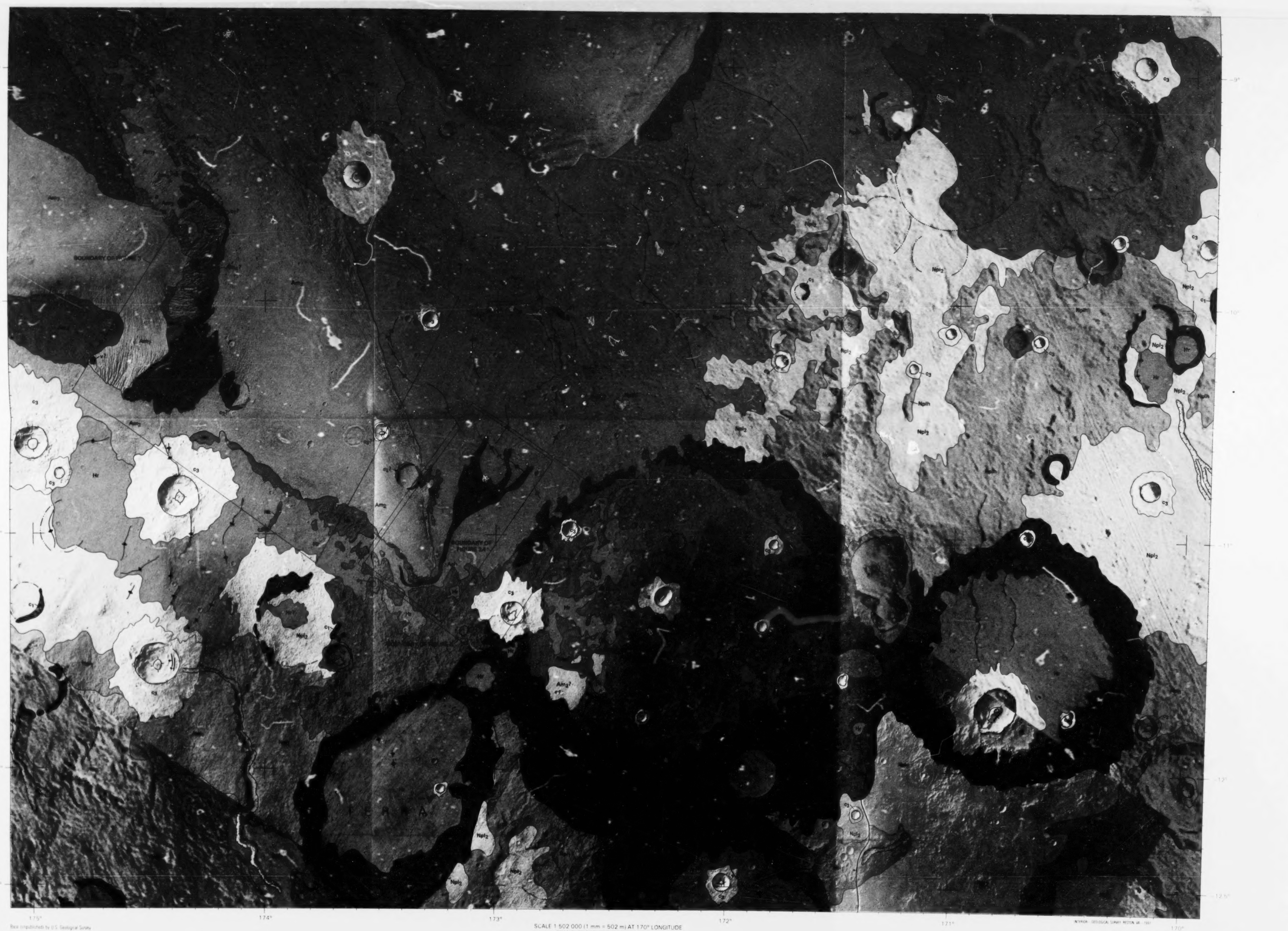
The prominent ridges (fig. 3) and intervening grooves carved on most members of the formation have been attributed in places to prevailing wind or paleowind erosion (Zimbelman and Wells, 1987; Schultz and Lutz, 1988). Scott and Tanaka (1982) noted that erosional patterns on one member of the formation follow the present dominant wind direction but that other members exhibit lineament sets intersecting at acute angles.

The orientation of grooves and ridges on members of the Medusae Fossae Formation and the present prevailing wind direction (indicated by bright streaks in the lee of surface obstacles) are shown in figure 4. Only major grooves and ridges on the oldest member (unit **Am₁**) are generally aligned with the wind direction; on all other members they are normal or nearly normal to it. Here, as well as elsewhere on the Medusae Fossae Formation (Scott and Tanaka, 1982), groove and ridge patterns commonly occur in sets that have acute junction angles. For this reason we interpret grooves and ridges as wind-erosion features scoured along complementary joint sets in formation members rather than as representations of variations in paleowind directions alone. Wrinkle ridges in ridged plains material largely follow the northwest-trending and best defined joint sets in members 2, 3, and 4 (fig. 4). This observation does not necessarily imply that the stress fields responsible for formation of both types of features were either similar or contemporaneous. (A fuller discussion is given in Structure.)

Channel and flood-plain material (unit **Ach**) is considered Early to Middle Amazonian in age because its enclosing channel cuts member 2 of the Medusae Fossae Formation (fig. 2A). Conspicuous erosional/depositional bedforms occur in its broad discharge area, which is large relative to the short, straight "upstream" reach of the channel (northeast of the tip of member 2).

ORIGIN OF AMAZONIAN CHANNEL

The morphology and geologic setting of the channel provide some constraints on its origin. Morphologically, it is a miniature analog of other Martian outflow channels.



Base compiled by U.S. Geological Survey

SCALE 1:502 000 (1 mm = 502 m) AT 170° LONGITUDE
TRANSVERSE MERCATOR PROJECTION

10 0 10 20 30 40 50 60 70 80 90 100
KILOMETERS

INTERIOR—GEOLOGICAL SURVEY, RESTON, VA—1991

Prepared on behalf of the Planetary Geology Program, Solar System Exploration Division, Office of Space Science, National Aeronautics and Space Administration, under contract W-15,814

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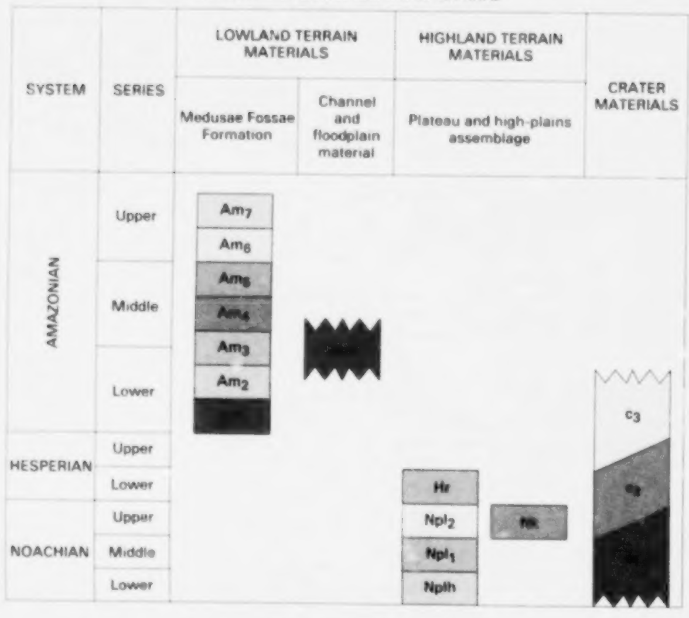
CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

[Geologic map units are described on the basis of morphologic characteristics observed on Viking Orbiter images. The origin and composition of these units are interpreted from their morphology and thus may be uncertain and controversial. Age relations are determined by stratigraphic positions and crater counts over a much larger region than the map area]

LOWLAND TERRAIN MATERIALS

Medusae Fossae Formation—Members form series of relatively smooth to grooved, massive, soft- to firm-appearing deposits without visible bedding. Surfaces gently inclined toward valley central to map area, flat to convex and gently rolling; moderate albedo; deeply eroded in places by wind, presumably along joint sets, producing grooves separated by yardangs (Ward, 1979). Morphologically resemble terrestrial sequences of welded and nonwelded ash flow tuffs (Scott and Tanaka, 1982, 1986) and are so interpreted here and throughout Memnonia region

Am$_7$ **Member 7**—Overlies all other members; surfaces smooth, convex, slightly grooved in places along margins; no superposed impact craters

Am$_6$ **Member 6**—Overlies members 5 and 4; surfaces pitted and partly grooved, flat, gently inclined toward central valley; a few small (<8 km diameter) degraded or partly buried craters

Am$_5$ **Member 5**—Overlies member 4; appears similar to member 6 but no craters visible

Am$_4$ **Member 4**—Overlies members 3, 2, and 1 and ridged plains material (unit Hr); surface smooth to slightly grooved; no craters visible

Am$_3$ **Member 3**—Overlies members 2 and 1; deeply grooved surfaces; no craters visible

Am$_2$ **Member 2**—Overlies member 1, ridged plains material, and knobby material; superposed small (<3 km diameter) craters and partly buried craters common. May overlie knobby unit on floor of large highland crater

Member 1—Small areal extent; surface deeply grooved. Relative age uncertain but probably Early Amazonian; appears embayed by member 2 and partly covers rim and floor of 8-km-diameter crater having sharp rim crest that suggests a c$_2$ (Hesperian) or younger crater age

Channel and flood-plain material—Forms channel floor, outwash plain, and bedforms in discharge area. *Interpretation:* Outflow channel deposits formed by rapid breakout of water impounded by member 2 of Medusae Fossae Formation; water may have transected tip of member 2

HIGHLAND TERRAIN MATERIALS

Plateau and high-plains assemblage

Hr **Ridged plains material**—Occurs on central valley floor and floors of c$_1$ and c$_2$ craters; smooth, relatively flat surface with curvilinear, northwest-trending ridges; moderately cratered. *Interpretation:* Lava flows probably erupted from fissure vents

Npl$_2$ **Subdued cratered material**—Forms plains marked by subdued and partly buried old crater rims. *Interpretation:* Thin mantle of lava flows and eolian deposits that partly bury underlying rocks

Nk **Knobby material**—Forms knobs and small rounded to partly streamlined hills commonly in linear arrays trending northwest; less hummocky and of lower albedo on floor of large highland crater centered at lat 11.5° S., long 172°. *Interpretation:* Volcanic material highly modified in central valley by fluvioglacial processes

Npl$_1$ **Cratered material**—Rough, irregular surface with buried and partly buried crater rims; transected in places by small valleys with medial channels. *Interpretation:* Mixture of lava flows, impact breccias, crater-rim material, and minor eolian and fluvial deposits

Nplh **Hilly material**—Similar to cratered material but contains more peaks and large ridges; buried crater outlines common. *Interpretation:* Same as cratered material but tectonic deformation greater

CRATER MATERIALS

[Impact craters are assigned relative ages on basis of recognizable morphologic appearance and superposition relations. Craters of c$_3$ age have sharp, fresh-appearing rim crests; most ejecta blankets extend about one crater diameter beyond rim crest. With increasing age, craters become progressively more degraded and subdued in appearance, and their ejecta deposits are discernible only relatively close to rim crest. On Correlation of Map Units, overlaps are indicated between crater age classes and time-stratigraphic boundaries. Craters with rim crests <3 km in diameter are not mapped]

c$_3$ **Material of craters having sharp rim crests**—Fresh-appearing craters having continuous rims and broad ejecta blankets; smaller craters bowl shaped; central peaks common; crater floors rough to smooth. Superposed on all highland terrain materials; queried occurrence on member 2 of Medusae Fossae Formation may be partly buried

c$_2$ **Material of subdued craters**—Moderately eroded craters having continuous or discontinuous, narrow rims; central peaks in places; floors rough or flat and smooth; queried where partly buried

Material of degraded craters—Deeply eroded craters; rims commonly incomplete; no central peaks; floors mostly covered by younger materials; remnants of craters <5 km in diameter not distinguishable

Contact—Dashed where approximately located

Fault—Bar and ball on downthrown side

Wrinkle ridge

Trough

Scarp—Barb points downslope

Depression

Possible caldera

Valley

Narrow channel

Catena—Chain of pit craters

Collapsed lava tube

Crater rim crest

Buried crater rim crest

Crater central peak

Crater central pit

b **Channel bar or island**

Volcano with summit crater—Age indeterminate, possibly Middle Amazonian or younger

Blocky material—Interpreted as landslide deposit

INTRODUCTION

The geologic map shows an area within the Memnonia region that has been proposed as a candidate landing site for a Mars sample return mission. Site-selection priorities are constrained by the terrain roughness, which may affect the descent of the landing craft and the mobility of the sampling vehicle. Evaluation of small-scale topographic features (<50 m of relief) can be made only in a very general way from available imagery. For this reason the candidate site in this map area is provisionally recommended primarily on the basis of its high scientific value; however, no adverse surface conditions are discernible in the site area at the resolution (~50 m/picture element) of Viking images.

Geologic studies of the site area made from computer-enhanced, high-resolution images show that rocks having a wide range of ages and inferred compositions are accessible to a roving vehicle. Geologic and other information obtained from samples of these rocks would fulfill many of the primary criteria that are necessary to advance our understanding of the evolutionary history of Mars (Scott and Tanaka, 1987; Scott, 1988). In addition, a recent fluvial episode is evidenced by a small channel in the site area that has incised materials emplaced during the Amazonian Period. The channel may have been carved by water mobilized from ice in the subjacent regolith by overriding ashflows (Scott and Chapman, 1989). The presence of this young channel has important implications for the possible occurrence and distribution of shallow ground water in the equatorial regions of Mars, as well as for Mars' climatic history.

Geologic mapping was compiled on a Viking 1:500,000-scale photomosaic base, and photoclinometric profiles were obtained over selected areas to investigate the shape of the channel and its bedforms. Map units generally correspond to those shown on the geologic map of the western equatorial region of Mars (Scott and Tanaka, 1986). In places, however, interpretations and contacts have been revised to reflect more detailed information visible on high-resolution Viking images that were enhanced by spatial filtering (Condit and Chavez, 1979).

GEOLOGIC SETTING

The map area is in the Memnonia northwest subquadrangle (MC-16NW; U.S. Geological Survey, 1986) and is centered in a valley between the Medusae Fossae Formation in the northern lowland plains and the southern highlands (fig. 1). These northern and southern provinces are global in extent and represent a physiographic and geologic dichotomy of the Martian crust. Several hypotheses have been advanced for the origin of the dichotomy (described under Structure). The valley floor is covered by ridged lava plains (Scott and Tanaka, 1982, 1986), which are overlain to the north by the Medusae Fossae Formation; members of the formation form a series of stepped plateaus rising northward to as much as about 2,000 m above the valley floor (U.S. Geological Survey, 1986). On the south side of the valley, the ridged plains embay the cratered highlands; here, as elsewhere on Mars, the ancient highlands consist of a mélange of rocks that include lava flows, impact breccias, and eolian and minor fluvial deposits. Large areas within the highlands have rough surfaces, formed by overlapping crater rims and ejecta blankets, that represent an impact history inherited from the early crustal development of Mars. Other parts of the highlands appear more subdued and smoothed where they have been resurfaced by lava flows and eolian mantles.

STRATIGRAPHY

The stratigraphic positions of map units have been established regionally and planetwide by previous investigations (Scott and Tanaka, 1986; Tanaka, 1986; Tanaka and others, 1988). Members of the Medusae Fossae Formation, however, have been further subdivided in the present work, and in places their position in sequence has been changed from that mapped by Scott and Tanaka (1982) at a smaller (1:2,000,000) scale. These subdivisions are based on stratigraphic relations and are mostly unsupported by crater counts because of the small areal extent of the units in the map area.

NOACHIAN SYSTEM

The densely cratered terrain in the southern part of the map area includes three of the seven major Noachian rock units that form the ancient Martian highlands (Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka and Scott, 1987). The hilly material (unit **Nplh**) lies at the base of the plateau and high plains assemblage and is characterized by rugged, generally isolated peaks and ridges. The hilly unit is not readily distinguished in places from cratered material (unit **Npl$_1$**), and their mapped boundaries are somewhat arbitrary. However, in the Memnonia region, the distribution of ridges and peaks in the hilly material is generally more even than that of features on the rough surface of the cratered unit. The strong relief of the hilly unit may be due largely to normal faulting, whereas the roughness of cratered terrain mostly arises from degraded, partly buried, and buried crater rims.

Large areas within the highlands were resurfaced in the Late Noachian by volcanic, eolian, fluvial, and mass-wasting processes that produced relatively smooth, mantled surfaces on the old material. The subdued cratered unit (unit **Npl$_2$**) has such surfaces: crater rims, ridges, and hills are recognizable beneath the mantle, but the coarse texture of intercrater areas is obscured.

Material having a knobby and hilly appearance (unit **Nk**) is assigned a Late Noachian age, but its assignment is provisional because its stratigraphic position is uncertain. The unit overlies rocks as young as Late Noachian (c$_1$ crater material and the subdued cratered unit), but it appears to be embayed by lava flows of the Lower Hesperian ridged plains material (unit Hr). However, the knobby unit also appears to be transitional in places with the basal part of member 2 (unit **Am$_2$**) of the Medusae Fossae Formation of Amazonian age. This ambiguity cannot be resolved by available Viking imagery. At the map scale, the knobby material appears coarse to fine textured and commonly lineated (fig. 2*A*); individual knobs and hills are about 100 to 500 m across. Where the unit occurs within the large (100-km-diameter), unnamed crater centered at lat 11.5° S., long 172.5°, it appears grossly dissected with a surface covered by small, evenly spaced hills; a lobe of the material extends into a calderalike depression on the crater floor. Around the southeast side of the depression, the knobs and small hills that elsewhere characterize the unit grade into relatively smooth terrain marked by a catena (a chain of pit craters), minor valleys, and tubelike ridges radiating from the rim of the calderalike landform. Although the knobby material in its various morphological aspects is mapped as a single unit, it may consist of several materials having different origins and ages. A volcanic origin and Noachian age are suggested by its lobate, flowlike margins, what appear to be collapsed lava tubes, and its occurrence in the large, ancient impact crater. The seemingly gradational relation of knobby material with a member of the Medusae Fossae Formation seems to indicate an Amazonian age and a possible pyroclastic origin. In other places, particularly in the valley around a small outflow channel (whose fill is mapped as unit **Ach**), the smaller knobs and hills occur both in linear arrays trending northwest and in clusters; the clusters resemble the beaded eskers and drumlin tracts of a glaciated landscape. These features, as well as the young outflow channel, suggest that postdepositional fluvioglacial processes might have been active during the Amazonian in this area.

HESPERIAN SYSTEM

The Hesperian marks the transition between the high impact cratering rate of the Noachian Period and the relatively low impact flux during Amazonian time (Neukum, 1987). For this reason, radiometric ages of Hesperian rock samples would be of great importance in establishing a Martian cratering chronology.

Ridged plains material (unit Hr) is one of the most extensive geologic units mapped on Mars (Scott and Tanaka, 1986; Greeley and Guest, 1987). The surface of the unit is smooth and level with long, widely spaced wrinkle ridges similar to those of the lunar maria; the unit is interpreted to consist of lava flows, probably basaltic, as are the lunar analogs. Ridged plains material also covers the floors of some c$_1$ and c$_2$ craters in the highlands and appears to embay the ejecta blanket of the 35-km-diameter c$_2$ crater centered near lat 9.3° S., long 170.4°.

AMAZONIAN SYSTEM

The Medusae Fossae Formation consists of seven members in the map area; their surfaces are flat to gently convex and, unlike most lava flows on Mars, do not have pressure ridges or lobate fronts on their margins. The formation has been eroded by wind into flutes and yardangs (Ward, 1979), which in places appear to follow complementary joint sets (fig. 3) similar to those in the more welded zones of terrestrial ignimbrites (Scott, 1969). Individual members of the formation do not exhibit the fine layering of Martian polar deposits or the bedding of some interior materials in Valles Marineris attributed to ash fallout or fluvial deposition (McCauley, 1978; Lucchitta, 1982). The formation makes up a broad but discontinuous belt (fig. 1) that trends east-west along the highland-lowland boundary from long 127° to 221°. Stratigraphic relations and crater counts outside the map area (Scott and Tanaka, 1982, 1986) indicate an Early to Late Amazonian age for members of the formation. On the basis of its morphologic characteristics, the Medusae Fossae Formation has been interpreted to consist of ash-flow tuffs (Malin, 1979; Ward, 1979; Scott and Tanaka, 1982, 1986). Other investigators, however, have considered it to be ancient polar deposits (Schultz and Lutz, 1988) or pyroclastic and eolian materials (Greeley and Guest, 1987). Absolute ages and mineralogies obtained from samples of the Medusae Fossae Formation would aid in defining the cratering chronology during the Amazonian Period and resolve the controversial origin of the formation.

Morphologic characteristics of the Medusae Fossae members are discussed in the Description of Map Units. Their respective stratigraphic positions are generally clearly shown in the map area by overlap relations. However, the position of the oldest member (unit **Am$_1$**) cannot be directly established with respect to ridged plains material (unit **Hr**), because the units have no common boundary in the map area. The oldest member is assumed to be of Amazonian age because elsewhere in the region it has been observed to overlie the ridged plains material (Scott and Tanaka, 1982, 1986; Greeley and Guest, 1987). Within the map area there is no surety that noncontiguous outcrops represent the same deposit even though their morphology and homotaxial relations may be similar.

The prominent ridges (fig. 3) and intervening grooves carved on most members of the formation have been attributed in places to prevailing wind or paleowind erosion (Zimbelman and Wells, 1987; Schultz and Lutz, 1988). Scott and Tanaka (1982) noted that erosional patterns on one member of the formation follow the present dominant wind direction but that other members exhibit lineament sets intersecting at acute angles.

The orientation of grooves and ridges on members of the Medusae Fossae Formation and the present prevailing wind direction (indicated by bright streaks in the lee of surface obstacles) are shown in figure 4. Only major grooves and ridges on the oldest member (unit **Am$_1$**) are generally aligned with the wind direction; on all other members they are normal or nearly normal to it. Here, as well as elsewhere on the Medusae Fossae Formation (Scott and Tanaka, 1982), groove and ridge patterns commonly occur in sets that have acute junction angles. For this reason we interpret grooves and ridges as wind-erosion features scoured along complementary joint sets in formation members rather than as representations of variations in paleowind directions alone. Wrinkle ridges in ridged plains material largely follow the northwest-trending and best defined joint sets in members 2, 3, and 4 (fig. 4). This observation does not necessarily imply that the stress fields responsible for formation of both types of features were either similar or contemporaneous. (A fuller discussion is given in Structure.)

Channel and flood-plain material (unit **Ach**) is considered Early to Middle Amazonian in age because its enclosing channel cuts member 2 of the Medusae Fossae Formation (fig. 2*A*). Conspicuous erosional/depositional bedforms occur in its broad discharge area, which is large relative to the short, straight "upstream" reach of the channel (northeast of the tip of member 2).

ORIGIN OF AMAZONIAN CHANNEL

The morphology and geologic setting of the channel provide some constraints on its origin. Morphologically, it is a miniature analog of other Martian outflow channels. However, the head of the channel is not associated with collapsed or chaotic terrain, as at Maja, Kasei, and Shalbatana Valles (Scott and Tanaka, 1986), nor with faults, as at Mangala Valles (fig. 1). The flood of water that carved the channel appears to have been catastrophic and of short duration, as indicated by its deeply eroded floor, prominent erosional bedforms, and absence of tributaries (fig. 2); the missing element, however, is a clearly defined source of the flow.

Although the absence of tributaries indicates that the channel was not produced by runoff from a well-developed drainage basin, the channel area can be divided into two of the three zones of terrestrial fluvial systems (Schumm, 1977, p. 3). As shown in figure 2*A*, zone 2 is the sediment- and water-transport zone that includes the major part of the stream, and zone 3 is the alluvial plain or deposition area. The hypothetical position of the beginning of zone 1 is indicated in the figure. (Ordinarily, zone 1 comprises the drainage basin and runoff-production area where tributaries are concentrated.) Because this zone is not present in the channel area, several hypotheses have been advanced (Scott and Chapman, 1989) regarding possible sources of the water flow. The most likely hypothesis is that ash flows melted ground ice in the subjacent regolith or bedrock. This process is predicated on the assumptions that the Medusae Fossae Formation consists of ash-flow tuffs, that ground ice was present in cracks and pores in the ridged plains or knobby materials underlying the ash flow, and that the flow was hot enough during emplacement to melt this ice.

The ridged plains unit and older materials are considered to have been prime storage reservoirs for interstitial ice contained in pores and fractures of breccias and lava flows or in weathered zones between flows (Chapman and Scott, 1989). Melting and mobilization of the ground ice by volcanic, tectonic, and impact processes appear to have initiated the floods that produced the large outflow channels that drained into Chryse Planitia (Carr, 1979). In the Memnonia area, the release of water from ground ice in the ridged plains or knobby units could have been activated by heat transfer from the ash flows. Melting would first occur where ice was closest to the surface. Hydrothermal circulation of water may have been induced in these materials, or vaporization pressure or lithostatic pressure generated by the overlying ash flows may have forced melt water to the surface. Most of this water probably accumulated in the valley above the spur of member 2 of the Medusae Fossae Formation (fig. 2*A*), which is thought to have projected across the course of the present channel and created a temporary dam. Water could have been released when its hydrostatic head produced rock failure in the weak, nonwelded ash flow or when it overtopped and breached the narrow barrier. That such a barrier existed is indicated by the abrupt termination of the frontal lobe of member 2, forming a cliff and terraces incised parallel to the channel gorge (fig. 2*A*, *B*). A knickpoint and a long plunge pool in the center of the channel (fig. 2*A*) indicate where, after the dam failed, the sudden rush of water caused a rapid lowering of base level. (The shape of the channel and its

GEOLOGIC MAP OF SCIENCE STUDY AREA 6, MEMNONIA REC

(MTM -10172)

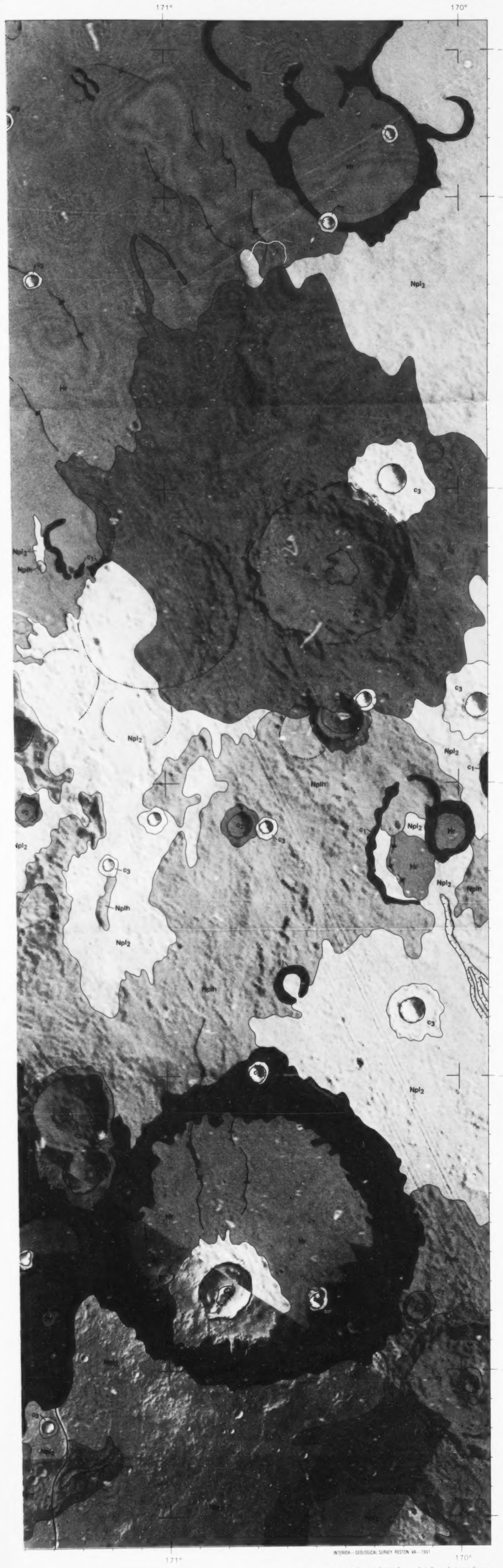
By

David H. Scott and Mary G. Chapman

1991

ATLAS OF MARS
1:500,000 GEOLOGIC SERIES
MEMNONIA REGION
M 500K -10/172 G, 1991
I-2084

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION



Prepared on behalf of the Planetary Geology Program, Solar System Exploration Division, Office of Space Science, National Aeronautics and Space Administration under contract W-15,814
Manuscript approved for publication, June 14, 1989

old material. The subdued cratered unit (unit Npl_2) has such
ms, ridges, and hills are recognizable beneath the mantle, but the
ntercrater areas is obscured.
g a knobby and hilly appearance (unit Nk) is assigned a Late Noachian
nent is provisional because its stratigraphic position is uncertain. The
s as young as Late Noachian (c_1 crater material and the subdued
it appears to be embayed by lava flows of the Lower Hesperian ridged
it Hr). However, the knobby unit also appears to be transitional in
al part of member 2 (unit Am_2) of the Medusae Fossae Formation of
his ambiguity cannot be resolved by available Viking imagery. At the
bby material appears coarse to fine textured and commonly lineated
knobs and hills are about 100 to 500 m across. Where the unit occurs
0 km-diameter), unnamed crater centered at lat 11.5° S., long 172.5°, it
ssected with a surface covered by small, evenly spaced hills; a lobe of
ds into a calderalike depression on the crater floor. Around the
he depression, the knobs and small hills that elsewhere characterize
relatively smooth terrain marked by a catena (a chain of pit craters),
l tubelike ridges radiating from the rim of the calderalike landform.
bby material in its various morphological aspects is mapped as a single
of several materials having different origins and ages. A volcanic origin
are suggested by its lobate, flowlike margins, what appear to be
es, and its occurrence in the large, ancient impact crater. The
nal relation of knobby material with a member of the Medusae Fossae
o indicate an Amazonian age and a possible pyroclastic origin. In other
in the valley around a small outflow channel (whose fill is mapped as
ller knobs and hills occur both in linear arrays trending northwest and
sters resemble the beaded eskers and drumlin tracts of a glaciated
features, as well as the young outflow channel, suggest that
uvioglacial processes might have been active during the Amazonian in

1987). Within the map area there is no surety that noncontiguous outcrops represent the same deposit even though their morphology and homotaxial relations may be similar.

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bedforms were investigated by photoclinometric profiles that were obtained over selected areas.)

This hypothesis cannot be fully developed because emplacement temperatures, cooling histories, original thicknesses of the ash flows, and depth to ground ice are unknown. Some of these parameters can be estimated in terrestrial ash flows of known composition and thickness by their degrees of welding and crystallization; plausible assumptions might be made for these and other factors pertaining to the Amazonian channel, but they are beyond the scope of this study.

Other possible origins for the channel involve (1) water that may have been entrained as a volatile component of ash flows, (2) subterranean springs that may have existed beneath the Medusae Fossae Formation, (3) water that was discharged into the valley from large canyons in the bordering highlands, and (4) water that was released from paleopolar deposits (Medusae Fossae Formation) to form channels during the warming period following the hypothetical shift of the poles from the equatorial region to their present position (Schultz and Lutz, 1988).

Hypotheses other than those noted above can probably be conceived to explain the origin and processes responsible for the development of this young channel. However, the primary factors in resolving this important problem are the origin and composition of the Medusae Fossae Formation, which can be determined only from returned samples.

STRUCTURE

The physiographic boundary between the highland and lowland provinces is obscured in places where large accumulations of the young Medusae Fossae Formation overlap onto ancient highland terrain (fig. 1). The origin of this crustal dichotomy is unknown, but processes that have been hypothesized include mantle convection associated with core formation (Wise and others, 1979), a giant impact that formed a huge basin in the north polar region (Wilhelms and Squyres, 1984), and extensive southward erosional retreat of the highland plateau (Scott, 1978; Hiller, 1979). Whatever the origin of the dichotomy, the boundary clearly separates relatively young, uncratered materials of the lowlands from the highly cratered, ancient, highland rock assemblages.

Within the map area, the valley between the Medusae Fossae Formation in the lowlands and the adjacent highlands may be synclinal, possibly formed by downwarping during the Amazonian Period. Some evidence for this correspondence between topography and structure is suggested by the configuration of the valley fill (ridged plains material); the surface of this material, presumably deposited as relatively level lava flows, is now gently inclined in places toward the central part of the valley. Some members of the Medusae Fossae Formation, particularly member 6, also appear to dip and thin valleyward, further suggesting, along with grooves developed from joint sets (fig. 3), that tectonic activity occurred during the Amazonian.

With the exception of a 65-km-long, fresh-appearing, normal fault centered near lat 12.3° S., long 171.4°, little diastrophism in the highlands can be recognized in the map area.

Northwest-trending scarps form sublinear contacts locally at the base of members 2 and 4 of the Medusae Fossae Formation. These scarps may be related to normal-fault displacements that have been subsequently modified by erosion and joint-block separation. Prominent wrinkle ridges on Hesperian ridged plains material are also oriented northwest, suggesting a causal relation between these two structural types as well as among the major grooves interpreted to have formed from joint sets (fig. 4). However, the faults, wrinkle ridges, and joints were unlikely to have formed concurrently during the Amazonian Period by similar stress fields. The existence of the ridges in the Hesperian Period is indicated in several places where they are overlapped by the Medusae Fossae Formation. Moreover, stresses producing normal faults and joints are extensional, whereas ridges, like folds, may largely be formed by compression (Howard and Muehlberger, 1973; Plescia and Golombek, 1986; Watters and Maxwell, 1986). Interpretations as to the origins of wrinkle ridges differ, however, and their occurrence in some areas has been attributed to lava intrusions and squeeze-ups along extension fractures and faults (Colton and others, 1972; Hodges, 1973; Scott, 1973; Young and others, 1973). Wrinkle ridges are also common on the Moon and Mercury and, although their origin remains obscure, they appear to have formed in conjunction with large deposits of volcanic material.

GEOLOGIC HISTORY

Following the accretion and impact cratering of the Martian crust during the high bombardment flux of the Early Noachian Epoch, endogenic or exogenic processes produced the Martian crustal dichotomy expressed by the highland and lowland regions. That the formation of their boundary predates the Hesperian Period is shown by overlaps of Lower Hesperian ridged plains material across the boundary both within and outside the map area. Resurfacing of the lowland plains occurred from the Early Hesperian through the Late Amazonian, largely by lava flows from many sources, including the Olympus-Tharsis volcanic province (Scott and Tanaka, 1980; Scott, 1982). An episode of local volcanism probably also occurred during the Noachian and Hesperian, producing the large, calderalike feature centered at lat 11.5° S., long 172° and possible associated lava flows.

Voluminous, areally extensive (2.2×10^6 km^2) ignimbrite deposits were postulated by Scott and Tanaka (1982) to have erupted in the Amazonian Period in an irregular east-west zone along the highland/lowland boundary. These deposits, mapped as the Medusae Fossae Formation, are represented in the map area by seven members. (The formation as a whole extends between long 127° and 221°, well beyond the boundaries shown in figure 1; Scott and Tanaka, 1982, 1986; Greeley and Guest, 1987.) Following the deposition of member 2, water mobilized from ground ice accumulated behind a tongue-shaped barrier formed by the southern tip of this member; subsequent breaching of this ash-flow dam produced an outflow of water that carved a narrow channel containing distributary landforms. The formation of this channel is the youngest recognizable event in the map area and one of the youngest on Mars.

A CANDIDATE LANDING SITE

ROVER TRAVERSES AND SAMPLE STATIONS

Eight primary objectives and six secondary objectives, or targets of opportunity, are located within 15 km of the landing site shown in figure 5; this site is thought to be the most favorable of several that could be selected in the map area. Traverse routes to the sample stations are provisionally laid out from the landing site, where contingency samples would be obtained; the routes appear to be relatively smooth and free of obstacles at image resolution (~50 m/pixel). However, much higher resolution images, possibly obtained from a Mars Observer or other missions, are considered necessary for the final selection of an optimum landing site and of rover traverses to the stations recommended for sampling.

The primary sample stations are numbered in table 1; targets of opportunity that might be sampled en route are indicated by letters. The landing and ascent sites are assumed to be the same or close together.

Like the candidate landing site in the Memnonia area, the other sites in the planned science study areas (fig. 6) maximize the probability of selecting samples that will answer the widest diversity of fundamental questions within reasonable mission constraints.

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Table 1. *Materials to be sampled on proposed landing-site traverses at primary sample stations (numbers) and secondary targets of opportunity (letters). Landing site (LS) and traverses shown in figure 5.*

Estimated minimum traverse distance
Sample description and geologic

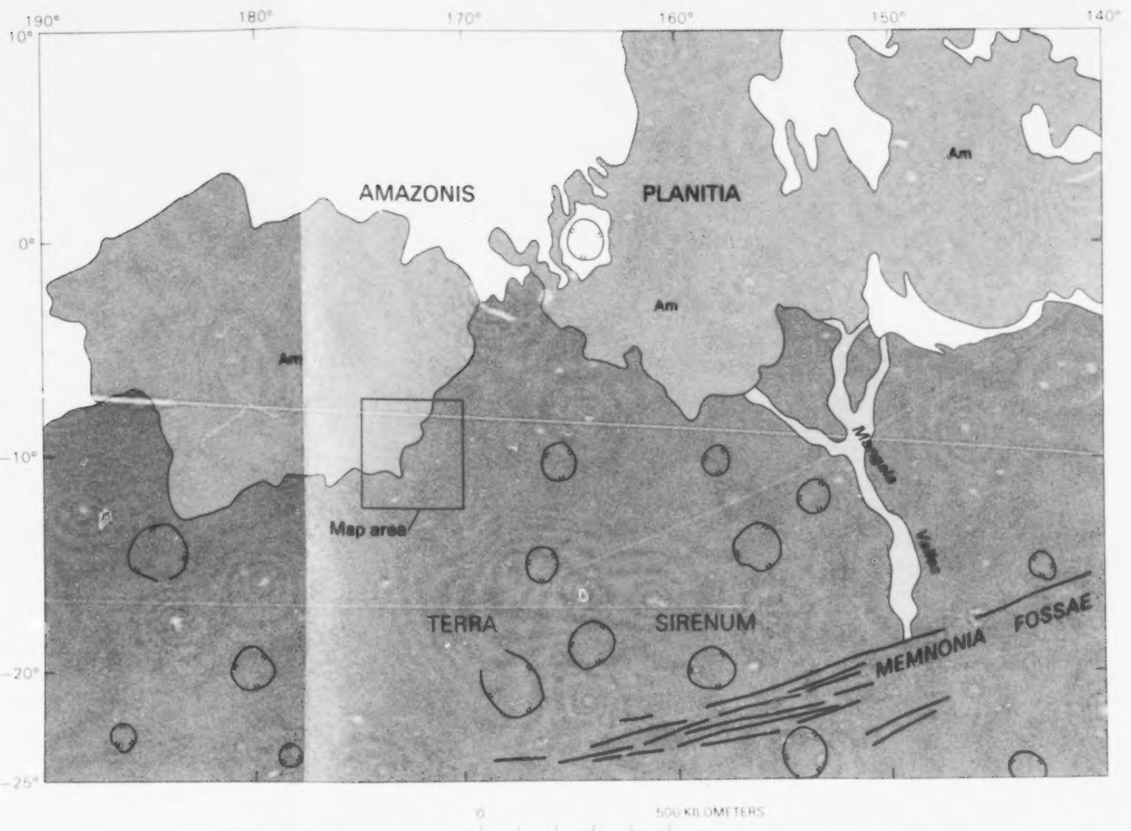
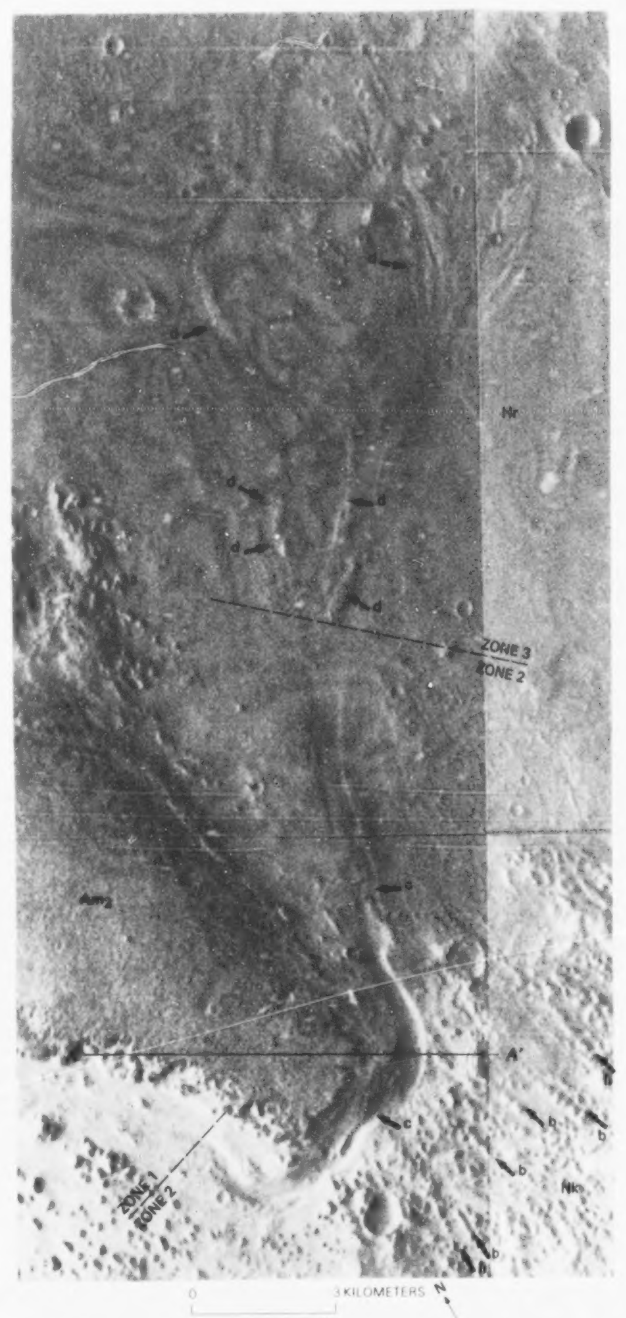


Figure 1. Index map showing location of map area in relation to major geologic features in this region of Mars. Medusae Fossae Formation (unit Am) has seven members in map area ranging from Early to Late Amazonian in age; formation lies across boundary between Noachian cratered highlands of Terra Sirenum and Amazonian relatively smooth lowlands of Amazonis Planitia. Large (>100-km-diameter) craters indicated by circular outlines, major faults and grabens by straight lines. Modified from Scott and Tanaka (1986).



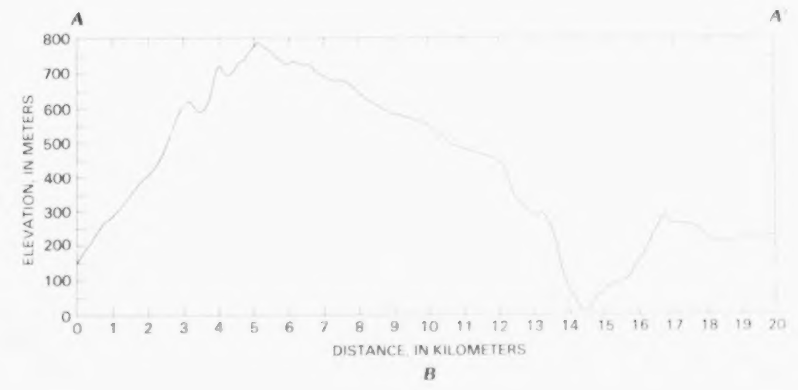


Figure 2. Geologic and hydrologic relations in area of small channel rounding tip of member 2 of Medusae Fossae Formation. **A**, Viking Orbiter image (centered at lat 11° S., long 173.2°). Knobby material (unit **Nk**) appears to be gradational with basal part of member 2 (unit Am_2); linear chains of hummocks (**b**) suggest fluvioglacial processes. Ridged plains material (unit **Hr**) forms floor of central valley. Channel zone 1 (a drainage and runoff production area with tributaries) is absent, but its hypothetical location is shown. (See text.) Channel zone 2 is major channel and sediment- and water-transport area with knickpoint (**c**) and associated plunge pool. Channel zone 3 is alluvial plain where sediment was deposited or bedrock eroded, indicated by distributaries and by streamlined bars (**d**). **A**-**A'** marks line of photoclinometric profile shown in **B**. **B**, Photoclinometric profile showing member 2 of Medusae Fossae Formation (0 to 14 km), plunge pool of young channel (14 to about 15 km), and surface of Noachian knobby unit (15 to 20 km).

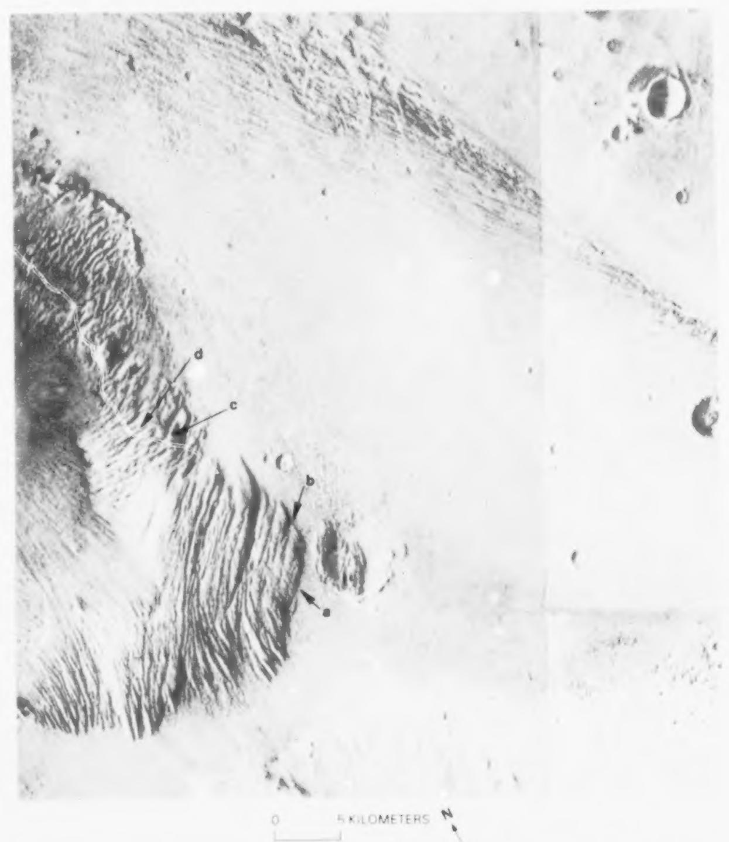


Figure 3. Ridges (yardangs) following joint sets in Medusae Fossae Formation. Ridges at a and b in member 1; ridges at c and d in member 3. Image centered at lat 10.3° S., long 174°.

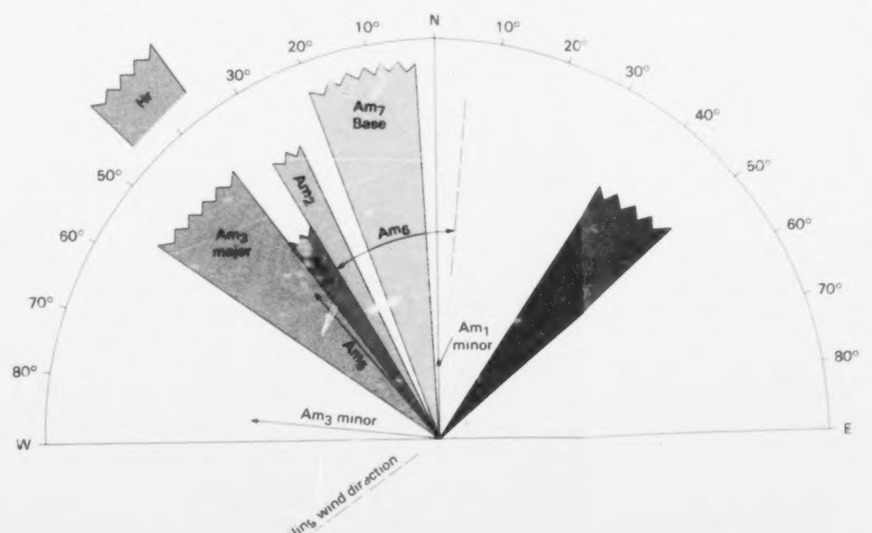


Figure 4. Orientation of major and minor grooves and ridges on members of Medusae Fossae Formation (units Am_1 through Am_7) and of most wrinkle ridges in ridged plains material (unit Hr).

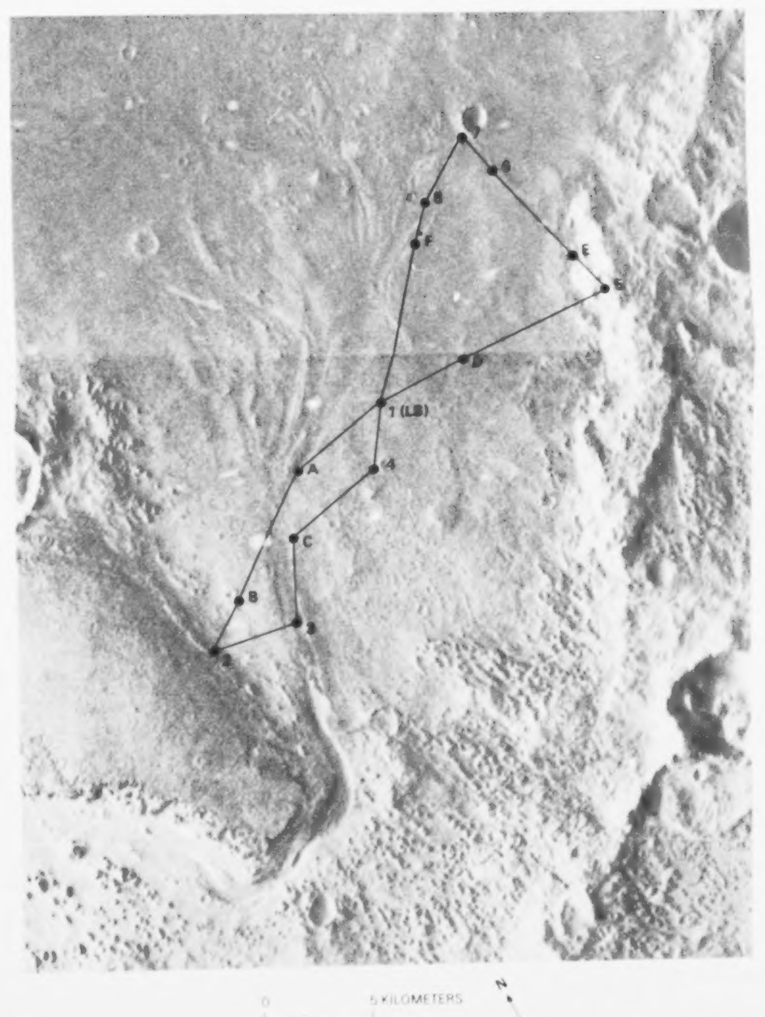
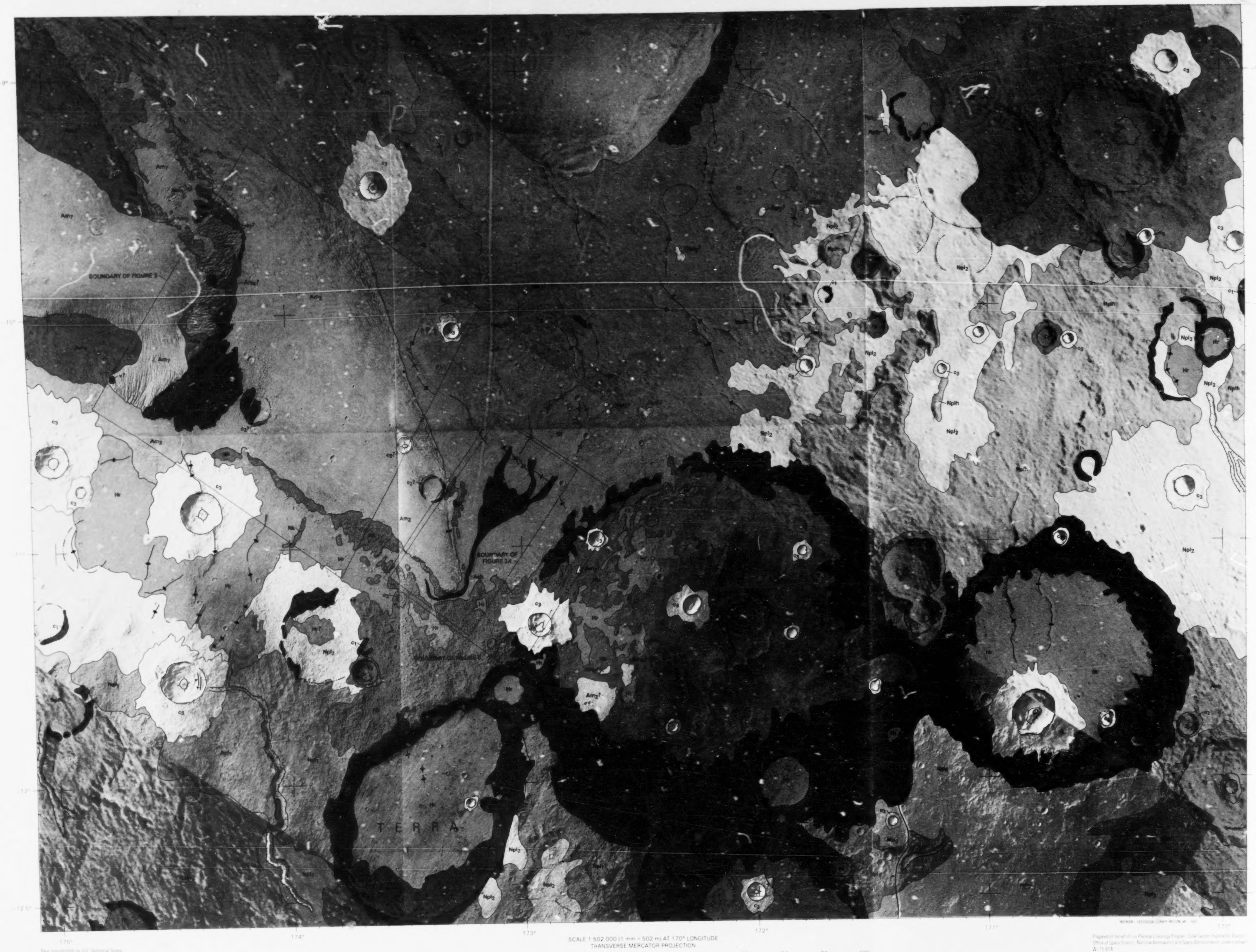


Figure 5. Proposed landing site (LS), rover traverses, and sample locations. Numbers mark primary sample locations; letters mark secondary target-of-opportunity sites. Samples and locations described in table 1.



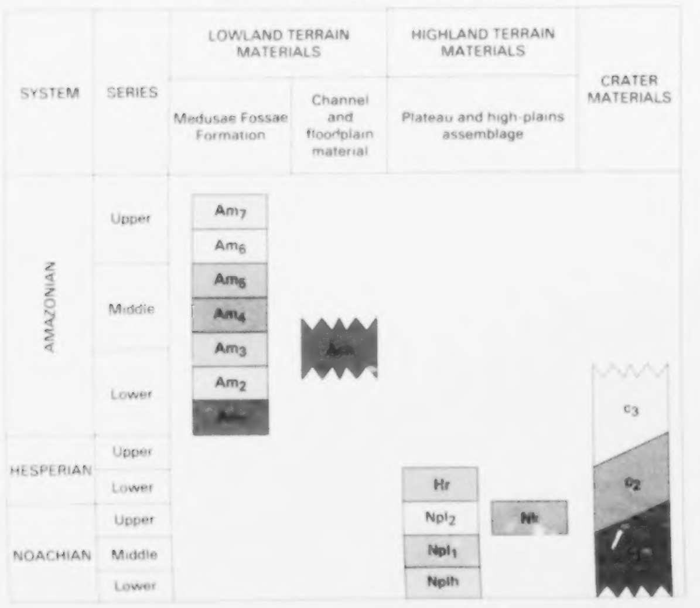
SCALE 1:502 000 (1 mm = 502 m) AT 170° LONGITUDE
TRANSVERSE MERCATOR PROJECTION

10 0 10 20 30 40 50 60 70 80 90 100

KILOMETERS

Manuscript approved for publication, June 14, 1991

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

[Geologic map units are described on the basis of morphologic characteristics observed on Viking Orbiter images. The origin and composition of these units are interpreted from their morphology and thus may be uncertain and controversial. Age relations are determined by stratigraphic positions and crater counts over a much larger region than the map area]

LOWLAND TERRAIN MATERIALS

Medusae Fossae Formation—Members form series of relatively smooth to grooved, massive, soft- to firm-appearing deposits without visible bedding. Surfaces gently inclined toward valley central to map area, flat to convex and gently rolling; moderate albedo; deeply eroded in places by wind, presumably along joint sets, producing grooves separated by yardangs (Ward, 1979). Morphologically resemble terrestrial sequences of welded and nonwelded ash-flow tuffs (Scott and Tanaka, 1982, 1986) and are so interpreted here and throughout Memnonia region

Am7 **Member 7**—Overlies all other members; surfaces smooth, convex, slightly grooved in places along margins; no superposed impact craters

Am6 **Member 6**—Overlies members 5 and 4; surfaces pitted and partly grooved, flat, gently inclined toward central valley; a few small (<8-km diameter) degraded or partly buried craters

Am5 **Member 5**—Overlies member 4; appears similar to member 6 but no craters visible

Am4 **Member 4**—Overlies members 3, 2, and 1 and ridged plains material (unit Hr); surface smooth to slightly grooved; no craters visible

Am3 **Member 3**—Overlies members 2 and 1; deeply grooved surfaces; no craters visible

Am2 **Member 2**—Overlies member 1, ridged plains material, and knobby material; superposed small (<3-km diameter) craters and partly buried craters common. May overlie knobby unit on floor of large highland crater

Member 1—Small areal extent; surface deeply grooved. Relative age uncertain but probably Early Amazonian; appears embayed by member 2 and partly covers rim and floor of 8-km-diameter crater having sharp rim crest that suggests a c2 (Hesperian) or younger crater age

Channel and flood-plain material—Forms channel floor, outwash plain, and bedforms in discharge area. *Interpretation*: Outflow channel deposits formed by rapid breakout of water impounded by member 2 of Medusae Fossae Formation; water may have transected tip of member 2

HIGHLAND TERRAIN MATERIALS

Plateau and high-plains assemblage

Hr **Ridged plains material**—Occurs on central valley floor and floors of c1 and c2 craters; smooth, relatively flat surface with curvilinear, northwest-trending ridges; moderately cratered. *Interpretation*: Lava flows probably erupted from fissure vents

Npl2 **Subdued cratered material**—Forms plains marked by subdued and partly buried old crater rims. *Interpretation*: Thin mantle of lava flows and eolian deposits that partly bury underlying rocks

Nk **Knobby material**—Forms knobs and small rounded to partly streamlined hills commonly in linear arrays trending northwest; less hummocky and of lower albedo on floor of large highland crater centered at lat 11.5° S., long 172°. *Interpretation*: Volcanic material highly modified in central valley by fluvioglacial processes

Npl1 **Cratered material**—Rough, irregular surface with buried and partly buried crater rims, transected in places by small valleys with medial channels. *Interpretation*: Mixture of lava flows, impact breccias, crater-rim material, and minor eolian and fluvial deposits

Nplh **Hilly material**—Similar to cratered material but contains more peaks and large ridges; buried crater outlines common. *Interpretation*: Same as cratered material but tectonic deformation greater

CRATER MATERIALS

[Impact craters are assigned relative ages on basis of recognizable morphologic appearance and superposition relations. Craters of c3 age have sharp, fresh-appearing rim crests; most ejecta blankets extend about one crater diameter beyond rim crest. With increasing age, craters become progressively more degraded and subdued in appearance, and their ejecta deposits are discernible only relatively close to rim crest. On Correlation of Map Units, overlaps are indicated between crater age classes and time-stratigraphic boundaries. Craters with rim crests <3 km in diameter are not mapped]

c3 **Material of craters having sharp rim crests**—Fresh-appearing craters having continuous rims and broad ejecta blankets; smaller craters bowl shaped; central peaks common; crater floors rough to smooth. Superposed on all highland terrain materials; queried occurrence on member 2 of Medusae Fossae Formation may be partly buried

c2 **Material of subdued craters**—Moderately eroded craters having continuous or discontinuous, narrow rims; central peaks in places; floors rough or flat and smooth; queried where partly buried

Material of degraded craters—Deeply eroded craters; rims commonly incomplete; no central peaks; floors mostly covered by younger materials; remnants of craters <5 km in diameter not distinguishable

Contact—Dashed where approximately located

Fault—Bar and ball on downthrown side

Wrinkle ridge

Trough

Scarp—Barb points downslope

Depression

- **Possible caldera**
- **Valley**

Narrow channel

Catena—Chain of pit craters

Collapsed lava tube

Crater rim crest

Buried crater rim crest

Crater central peak

Crater central pit

b **Channel bar or island**

v **Volcano with summit crater**—Age indeterminate, possibly Middle Amazonian or younger

Blocky material—Interpreted as landslide deposit

INTRODUCTION

The geologic map shows an area within the Memnonia region that has been proposed as a candidate landing site for a Mars sample-return mission. Site-selection priorities are constrained by the terrain roughness, which may affect the descent of the landing craft and the mobility of the sampling vehicle. Evaluation of small-scale topographic features (<50 m of relief) can be made only in a very general way from available imagery. For this reason the candidate site in this map area is provisionally recommended primarily on the basis of its high scientific value; however, no adverse surface conditions are discernible in the site area at the resolution (~50 m/picture element) of Viking images.

Geologic studies of the site area made from computer-enhanced, high-resolution images show that rocks having a wide range of ages and inferred compositions are accessible to a roving vehicle. Geologic and other information obtained from samples of these rocks would fulfill many of the primary criteria that are necessary to advance our understanding of the evolutionary history of Mars (Scott and Tanaka, 1987; Scott, 1988). In addition, a recent fluvial episode is evidenced by a small channel in the site area that has incised materials emplaced during the Amazonian Period. The channel may have been carved by water mobilized from ice in the subjacent regolith by overriding ashflows (Scott and Chapman, 1989). The presence of this young channel has important implications for the possible occurrence and distribution of shallow ground water in the equatorial regions of Mars, as well as for Mars' climatic history.

Geologic mapping was compiled on a Viking 1:500,000-scale photomosaic base, and photoclinometric profiles were obtained over selected areas to investigate the shape of the channel and its bedforms. Map units generally correspond to those shown on the geologic map of the western equatorial region of Mars (Scott and Tanaka, 1986). In places, however, interpretations and contacts have been revised to reflect more detailed information visible on high-resolution Viking images that were enhanced by spatial filtering (Condit and Chavez, 1979).

GEOLOGIC SETTING

The map area is in the Memnonia northwest subquadrangle (MC-16NW; U.S. Geological Survey, 1986) and is centered in a valley between the Medusae Fossae Formation in the northern lowland plains and the southern highlands (fig. 1). These northern and southern provinces are global in extent and represent a physiographic and geologic dichotomy of the Martian crust. Several hypotheses have been advanced for the origin of the dichotomy (described under Structure). The valley floor is covered by ridged lava plains (Scott and Tanaka, 1982, 1986), which are overlain to the north by the Medusae Fossae Formation; members of the formation form a series of stepped plateaus rising northward to as much as about 2,000 m above the valley floor (U.S. Geological Survey, 1986). On the south side of the valley, the ridged plains embay the cratered highlands; here, as elsewhere on Mars, the ancient highlands consist of a mélange of rocks that include lava flows, impact breccias, and eolian and minor fluvial deposits. Large areas within the highlands have rough surfaces, formed by overlapping crater rims and ejecta blankets, that represent an impact history inherited from the early crustal development of Mars. Other parts of the highlands appear more subdued and smoothed where they have been resurfaced by lava flows and eolian mantles.

STRATIGRAPHY

The stratigraphic positions of map units have been established regionally and planetwide by previous investigations (Scott and Tanaka, 1986; Tanaka, 1986; Tanaka and others, 1988). Members of the Medusae Fossae Formation, however, have been further subdivided in the present work, and in places their position in sequence has been changed from that mapped by Scott and Tanaka (1982) at a smaller (1:2,000,000) scale. These subdivisions are based on stratigraphic relations and are mostly unsupported by crater counts because of the small areal extent of the units in the map area.

NOACHIAN SYSTEM

The densely cratered terrain in the southern part of the map area includes three of the seven major Noachian rock units that form the ancient Martian highlands (Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka and Scott, 1987). The hilly material (unit **Nplh**) lies at the base of the plateau and high-plains assemblage and is characterized by rugged, generally isolated peaks and ridges. The hilly unit is not readily distinguished in places from cratered material (unit **Npl1**), and their mapped boundaries are somewhat arbitrary. However, in the Memnonia region, the distribution of ridges and peaks in the hilly material is generally more even than that of features on the rough surface of the cratered unit. The strong relief of the hilly unit may be due largely to normal faulting, whereas the roughness of cratered terrain mostly arises from degraded, partly buried, and buried crater rims.

Large areas within the highlands were resurfaced in the Late Noachian by volcanic, eolian, fluvial, and mass-wasting processes that produced relatively smooth, mantled surfaces on the old material. The subdued cratered unit (unit **Npl2**) has such surfaces: crater rims, ridges, and hills are recognizable beneath the mantle, but the coarse texture of intercrater areas is obscured.

Material having a knobby and hilly appearance (unit **Nk**) is assigned a Late Noachian age, but its assignment is provisional because its stratigraphic position is uncertain. The unit overlies rocks as young as Late Noachian (c1 crater material and the subdued cratered unit), but it appears to be embayed by lava flows of the Lower Hesperian ridged plains material (unit Hr). However, the knobby unit also appears to be transitional in places with the basal part of member 2 (unit **Am2**) of the Medusae Fossae Formation of Amazonian age. This ambiguity cannot be resolved by available Viking imagery. At the map scale, the knobby material appears coarse to fine textured and commonly lineated (fig. 2A); individual knobs and hills are about 100 to 500 m across. Where the unit occurs within the large (100-km-diameter), unnamed crater centered at lat 11.5° S., long 172.5°, it appears grossly dissected with a surface covered by small, evenly spaced hills; a lobe of the material extends into a calderalike depression on the crater floor. Around the southeast side of the depression, the knobs and small hills that elsewhere characterize the unit grade into relatively smooth terrain marked by a catena (a chain of pit craters), minor valleys, and tubelike ridges radiating from the rim of the calderalike landform. Although the knobby material in its various morphological aspects is mapped as a single unit, it may consist of several materials having different origins and ages. A volcanic origin and Noachian age are suggested by its lobate, flowlike margins, what appear to be collapsed lava tubes, and its occurrence in the large, ancient impact crater. The seemingly gradational relation of knobby material with a member of the Medusae Fossae Formation seems to indicate an Amazonian age and a possible pyroclastic origin. In other places, particularly in the valley around a small outflow channel (whose fill is mapped as unit **Ach**), the smaller knobs and hills occur both in linear arrays trending northwest and in clusters; the clusters resemble the beaded eskers and drumlin tracts of a glaciated landscape. These features, as well as the young outflow channel, suggest that postdepositional fluvioglacial processes might have been active during the Amazonian in this area.

HESPERIAN SYSTEM

The Hesperian marks the transition between the high impact cratering rate of the Noachian Period and the relatively low impact flux during Amazonian time (Neukum, 1987). For this reason, radiometric ages of Hesperian rock samples would be of great importance in establishing a Martian cratering chronology.

Ridged plains material (unit **Hr**) is one of the most extensive geologic units mapped on Mars (Scott and Tanaka, 1986; Greeley and Guest, 1987). The surface of the unit is smooth and level with long, widely spaced wrinkle ridges similar to those of the lunar maria; the unit is interpreted to consist of lava flows, probably basaltic, as are the lunar analogs. Ridged plains material also covers the floors of some c1 and c2 craters in the highlands and appears to embay the ejecta blanket of the 35-km-diameter c2 crater centered near lat 9.1° S., long 170.4°.

AMAZONIAN SYSTEM

The Medusae Fossae Formation consists of seven members in the map area; their surfaces are flat to gently convex and, unlike most lava flows on Mars, do not have pressure ridges or lobate fronts on their margins. The formation has been eroded by wind into flutes and yardangs (Ward, 1979), which in places appear to follow complementary joint sets (fig. 3) similar to those in the more welded zones of terrestrial ignimbrites (Scott, 1969). Individual members of the formation do not exhibit the fine layering of Martian polar deposits or the bedding of some interior materials in Valles Marineris attributed to ash fallout or fluvial deposition (McCauley, 1978; Lucchitta, 1982). The formation makes up a broad but discontinuous belt (fig. 1) that trends east-west along the highland-lowland boundary from long 127° to 221°. Stratigraphic relations and crater counts outside the map area (Scott and Tanaka, 1982, 1986) indicate an Early to Late Amazonian age for members of the formation. On the basis of its morphologic characteristics, the Medusae Fossae Formation has been interpreted to consist of ash-flow tuffs (Malin, 1979; Ward, 1979; Scott and Tanaka, 1982, 1986). Other investigators, however, have considered it to be ancient polar deposits (Schultz and Lutz, 1988) or pyroclastic and eolian materials (Greeley and Guest, 1987). Absolute ages and mineralogies obtained from samples of the Medusae Fossae Formation would aid in defining the cratering chronology during the Amazonian Period and resolve the controversial origin of the formation.

Morphologic characteristics of the Medusae Fossae members are discussed in the Description of Map Units. Their respective stratigraphic positions are generally clearly shown in the map area by overlap relations. However, the position of the oldest member (unit **Am1**) cannot be directly established with respect to ridged plains material (unit *Hr*), because the units have no common boundary in the map area. The oldest member is assumed to be of Amazonian age because elsewhere in the region it has been observed to overlie the ridged plains material (Scott and Tanaka, 1982, 1986; Greeley and Guest, 1987). Within the map area there is no surety that noncontiguous outcrops represent the same deposit even though their morphology and homotaxial relations may be similar.

The prominent ridges (fig. 3) and intervening grooves carved on most members of the formation have been attributed in places to prevailing wind or paleowind erosion (Zimbelman and Wells, 1987; Schultz and Lutz, 1988). Scott and Tanaka (1982) noted that erosional patterns on one member of the formation follow the present dominant wind direction but that other members exhibit lineament sets intersecting at acute angles.

The orientation of grooves and ridges on members of the Medusae Fossae Formation and the present prevailing wind direction (indicated by bright streaks in the lee of surface obstacles) are shown in figure 4. Only major grooves and ridges on the oldest member (unit **Am1**) are generally aligned with the wind direction; on all other members they are normal or nearly normal to it. Here, as well as elsewhere on the Medusae Fossae Formation (Scott and Tanaka, 1982), groove and ridge patterns commonly occur in sets that have acute junction angles. For this reason we interpret grooves and ridges as wind-erosion features scoured along complementary joint sets in formation members rather than as representations of variations in paleowind directions alone. Wrinkle ridges in ridged plains material largely follow the northwest-trending and best defined joint sets in members 2, 3, and 4 (fig. 4). This observation does not necessarily imply that the stress fields responsible for formation of both types of features were either similar or contemporaneous. (A fuller discussion is given in Structure.)

Channel and flood-plain material (unit **Ach**) is considered Early to Middle Amazonian in age because its enclosing channel cuts member 2 of the Medusae Fossae Formation (fig. 2A). Conspicuous erosional/depositional bedforms occur in its broad discharge area, which is large relative to the short, straight "upstream" reach of the channel (northeast of the tip of member 2).

ORIGIN OF AMAZONIAN CHANNEL

The morphology and geologic setting of the channel provide some constraints on its origin. Morphologically, it is a miniature analog of other Martian outflow channels. However, the head of the channel is not associated with collapsed or chaotic terrain, as at Maja, Kasei, and Shalbatana Valles (Scott and Tanaka, 1986), nor with faults, as at Mangala Valles (fig. 1). The flood of water that carved the channel appears to have been catastrophic and of short duration, as indicated by its deeply eroded floor, prominent erosional bedforms, and absence of tributaries (fig. 2); the missing element, however, is a clearly defined source of the flow.

Although the absence of tributaries indicates that the channel was not produced by runoff from a well-developed drainage basin, the channel area can be divided into two of the three zones of terrestrial fluvial systems (Schumm, 1977, p. 3). As shown in figure 2A, zone 2 is the sediment- and water-transport zone that includes the major part of the stream, and zone 3 is the alluvial plain or deposition area. The hypothetical position of the beginning of zone 1 is indicated in the figure. (Ordinarily, zone 1 comprises the drainage basin and runoff-production area where tributaries are concentrated.) Because this zone is not present in the channel area, several hypotheses have been advanced (Scott and Chapman, 1989) regarding possible sources of the water flow. The most likely hypothesis is that ash flows melted ground ice in the subjacent regolith or bedrock. This process is predicated on the assumptions that the Medusae Fossae Formation consists of ash-flow tuffs, that ground ice was present in cracks and pores in the ridged plains or knobby materials underlying the ash flow, and that the flow was hot enough during emplacement to melt this ice.

The ridged plains unit and older materials are considered to have been prime storage reservoirs for interstitial ice contained in pores and fractures of breccias and lava flows or in weathered zones between flows (Chapman and Scott, 1989). Melting and mobilization of the ground ice by volcanic, tectonic, and impact processes appear to have initiated the floods that produced the large outflow channels that drained into Chryse Planitia (Carr, 1979). In the Memnonia area, the release of water from ground ice in the ridged plains or knobby units could have been activated by heat transfer from the ash flows. Melting would first occur where ice was closest to the surface. Hydrothermal circulation of water may have been induced in these materials, or vaporization pressure or lithostatic pressure generated by the overlying ash flows may have forced melt water to the surface. Most of this water probably accumulated in the valley above the spur of member 2 of the Medusae Fossae Formation (fig. 2A), which is thought to have projected across the course of the present channel and created a temporary dam. Water could have been released when its hydrostatic head produced rock failure in the weak, nonwelded ash flow or when it overtopped and breached the narrow barrier. That such a barrier existed is indicated by the abrupt termination of the frontal lobe of member 2, forming a cliff and terraces incised parallel to the channel gorge (fig. 2A, B). A knickpoint and a long plunge pool in the center of the channel (fig. 2A) indicate where, after the dam failed, the sudden rush of water caused a rapid lowering of base level. (The shape of the channel and its

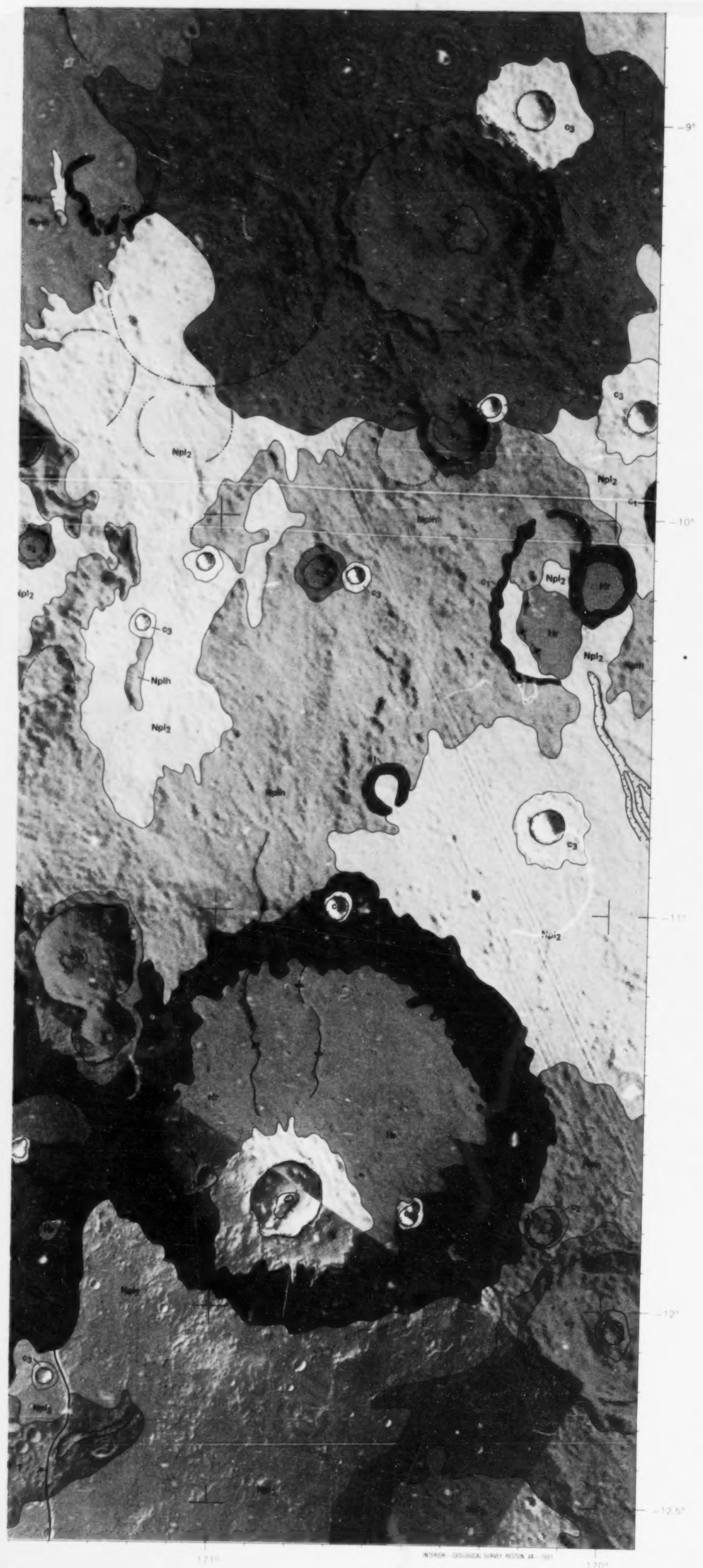
GEOLOGIC MAP OF SCIENCE STUDY AREA 6, MEMNONIA REC

(MTM -10172)

By

David H. Scott and Mary G. Chapman

1991



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12.3° S., long 171.4°, little diastrophism in the highlands can be recognized in the map area.

Northwest-trending scarps form sublinear contacts locally at the base of members 2 and 4 of the Medusae Fossae Formation. These scarps may be related to normal-fault displacements that have been subsequently modified by erosion and joint-block separation. Prominent wrinkle ridges on Hesperian ridged plains material are also oriented northwest, suggesting a causal relation between these two structural types as well as among the major grooves interpreted to have formed from joint sets (fig. 4). However, the faults, wrinkle ridges, and joints were unlikely to have formed concurrently during the Amazonian Period by similar stress fields. The existence of the ridges in the Hesperian Period is indicated in several places where they are overlapped by the Medusae Fossae Formation. Moreover, stresses producing normal faults and joints are extensional, whereas ridges, like folds, may largely be formed by compression (Howard and Muehlberger, 1973; Plescia and Golombek, 1986; Watters and Maxwell, 1986). Interpretations as to the origins of wrinkle ridges differ, however, and their occurrence in some areas has been attributed to lava intrusions and squeeze-ups along extension fractures and faults (Colton and others, 1972; Hodges, 1973; Scott, 1973; Young and others, 1973). Wrinkle ridges are also common on the Moon and Mercury and, although their origin remains obscure, they appear to have formed in conjunction with large deposits of volcanic material.

GEOLOGIC HISTORY

Following the accretion and impact cratering of the Martian crust during the high bombardment flux of the Early Noachian Epoch, endogenic or exogenic processes produced the Martian crustal dichotomy expressed by the highland and lowland regions. That the formation of their boundary predates the Hesperian Period is shown by overlaps of Lower Hesperian ridged plains material across the boundary both within and outside the map area. Resurfacing of the lowland plains occurred from the Early Hesperian through the Late Amazonian, largely by lava flows from many sources, including the Olympus-Tharsis volcanic province (Scott and Tanaka, 1980; Scott, 1982). An episode of local volcanism probably also occurred during the Noachian and Hesperian, producing the large, calderalike feature centered at lat 11.5° S., long 172° and possible associated lava flows.

Voluminous, areally extensive (2.2×10^6 km^2) ignimbrite deposits were postulated by Scott and Tanaka (1982) to have erupted in the Amazonian Period in an irregular east-west zone along the highland-lowland boundary. These deposits, mapped as the Medusae Fossae Formation, are represented in the map area by seven members. (The formation as a whole extends between long 127° and 221°, well beyond the boundaries shown in figure 1; Scott and Tanaka, 1982, 1986; Greeley and Guest, 1987.) Following the deposition of member 2, water mobilized from ground ice accumulated behind a tongue-shaped barrier formed by the southern tip of this member; subsequent breaching of this ash-flow dam produced an outflow of water that carved a narrow channel containing distributary landforms. The formation of this channel is the youngest recognizable event in the map area and one of the youngest on Mars.

A CANDIDATE LANDING SITE

ROVER TRAVERSES AND SAMPLE STATIONS

Eight primary objectives and six secondary objectives, or targets of opportunity, are located within 15 km of the landing site shown in figure 5; this site is thought to be the most favorable of several that could be selected in the map area. Traverse routes to the sample stations are provisionally laid out from the landing site, where contingency samples would be obtained; the routes appear to be relatively smooth and free of obstacles at image resolution (~50 m/pixel). However, much higher resolution images, possibly obtained from a Mars Observer or other missions, are considered necessary for the final selection of an optimum landing site and of rover traverses to the stations recommended for sampling.

The primary sample stations are numbered in table 1; targets of opportunity that might be sampled en route are indicated by letters. The landing and ascent sites are assumed to be the same or close together.

Like the candidate landing site in the Memnonia area, the other sites in the planned science study areas (fig. 6) maximize the probability of selecting samples that will answer the widest diversity of fundamental questions within reasonable mission constraints.

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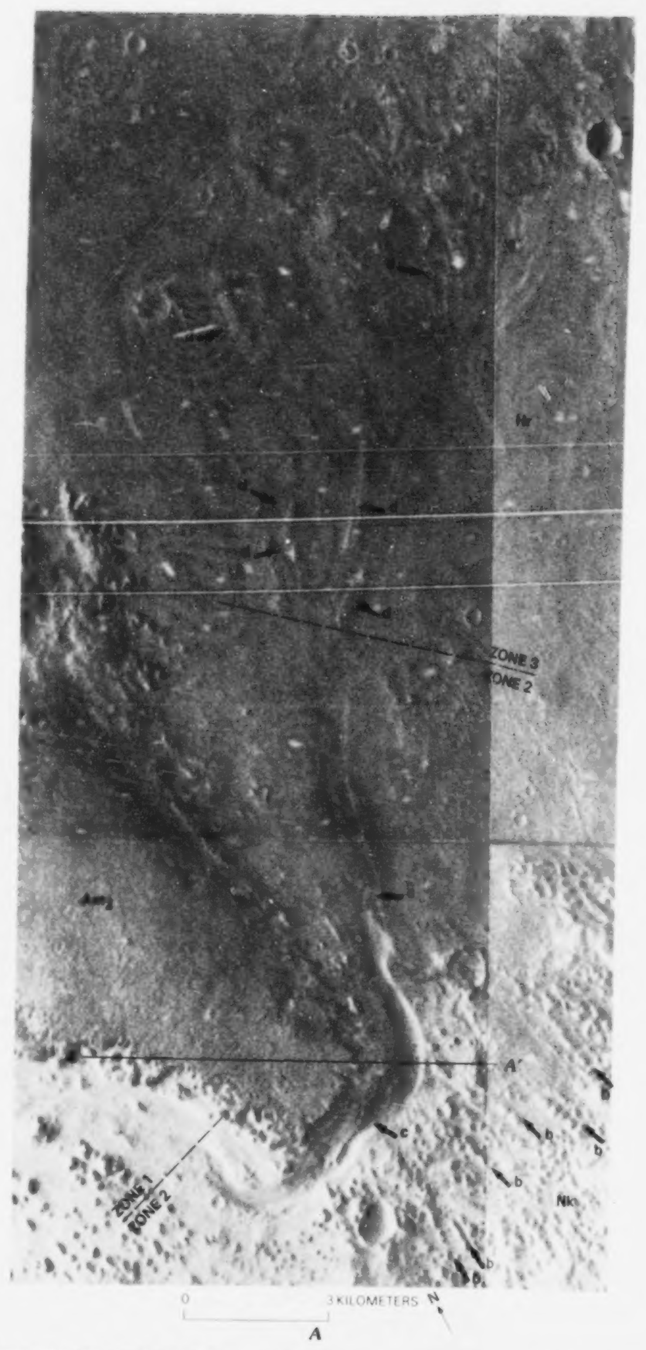
Table 1. *Materials to be sampled on proposed landing site traverses at primary sample stations (numbers) and secondary targets of opportunity (letters). Landing site (LS) and traverses shown in figure 5*

Station/Target	Estimated minimum traverse distance from LS (km)	Sample description and geologic significance
1 (LS)	0	Basalt flows of intermediate age (unit **Hr**); widespread occurrences, globally correlative geologically and by crater counts
A	6	Channel material (unit **Ach**) in bar or island remnant; TV scan for layering, sorting, size distribution
B	13	Knobby material (unit **Nk**)
2	16	Member 2 (unit **Am$_2$**) of Medusae Fossae Formation (young ash flow); TV scan to determine nature of contact with adjacent basalt flows (unit **Hr**) and knobby material (unit **Nk**)
3	21	Channel gorge cutting possible layered basalt flows (unit **Hr**) and older rocks
C	26	Samples and TV scan along channel from station 3 to C to observe possible layering of basalt flows in channel wall
4	32	Ejecta and rim material around 500-m-diameter crater in ridged plains unit
1 (LS)	35	Completion of first traverse
D	5	Ejecta and rim material around 600-m-diameter crater in ridged plains unit
5	14	Rim of Noachian (c$_1$) crater
E	16	Ridged plains/c$_1$ contact from station 5 to E
6	23	Wrinkle ridge in ridged plains unit; TV observation of ridge structure
7	25	Ejecta and rim material from young crater (1,500 m in diameter) in ridged plains unit
8	29	Fresh crater (300 m in diameter) superposed on channel material and on basalt of ridged plains unit
F	31	Channel material
1 (LS)	40	Completion of second traverse
	75 km	Total distance of two traverses

Figure 1. Index map showing location of map area in relation to major geologic features in this region of Mars. Medusae Fossae Formation (unit **Am**) has seven members in map area ranging from Early to Late Amazonian in age; formation lies across boundary between Noachian cratered highlands of Terra Sirenum and Amazonian relatively smooth lowlands of Amazonis Planitia. Large (>100-km-diameter) craters indicated by circular outlines, major faults and grabens by straight lines. Modified from Scott and Tanaka (1986).



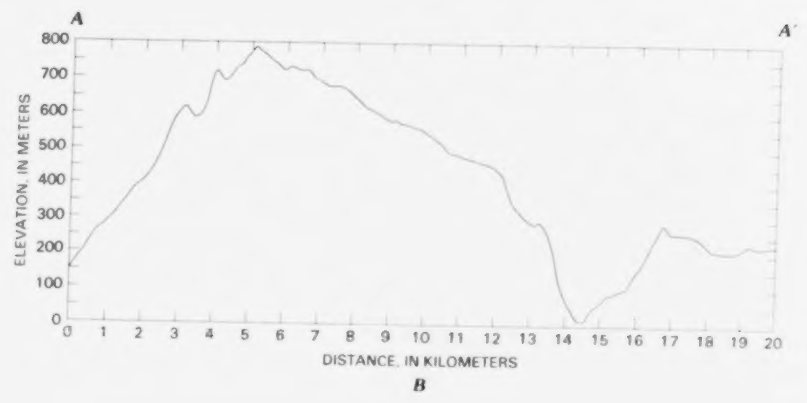


Figure 2. Geologic and hydrologic relations in area of small channel rounding tip of member 2 of Medusae Fossae Formation. ***A***, Viking Orbiter image (centered at lat 11° S., long 173.2°). Knobby material (unit **Nk**) appears to be gradational with basal part of member 2 (unit **Am$_2$**); linear chains of hummocks (**b**) suggest fluvioglacial processes. Ridged plains material (unit **Hr**) forms floor of central valley. Channel zone 1 (a drainage and runoff production area with tributaries) is absent, but its hypothetical location is shown. (See text.) Channel zone 2 is major channel and sediment- and water-transport area with knickpoint (**c**) and associated plunge pool. Channel zone 3 is alluvial plain where sediment was deposited or bedrock eroded, indicated by distributaries and by streamlined bars (**d**). ***A-A'*** marks line of photoclinometric profile shown in ***B***. ***B***, Photoclinometric profile showing member 2 of Medusae Fossae Formation (0 to 14 km), plunge pool of young channel (14 to about 15 km), and surface of Noachian knobby unit (15 to 20 km).

Figure 3. Ridges (yardangs) following joint sets in Medusae Fossae Formation. Ridges at **a** and **b** in member 1; ridges at **c** and **d** in member 3. Image centered at lat 10.3° S., long 174°.

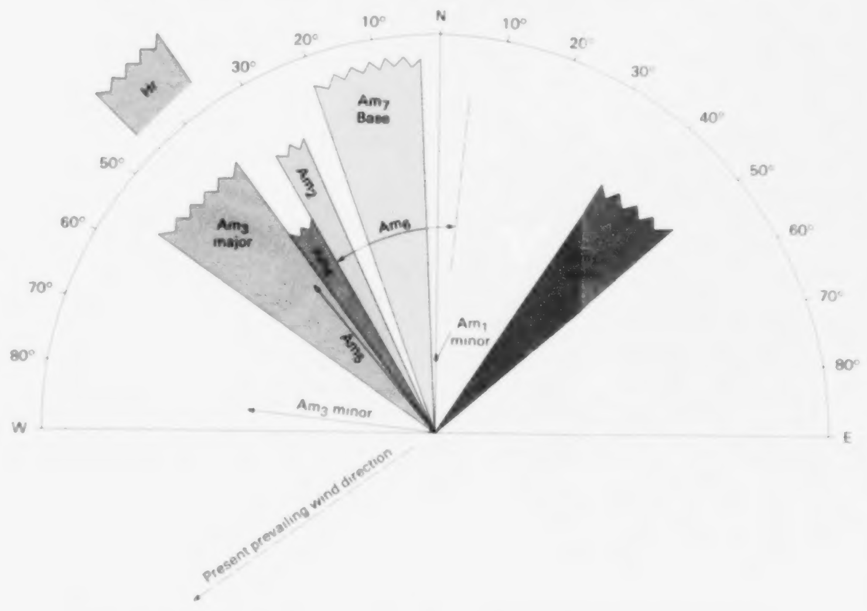


Figure 4. Orientation of major and minor grooves and ridges on members of Medusae Fossae Formation (units **Am$_1$** through **Am$_7$**) and of most wrinkle ridges in ridged plains material (unit **Hr**).

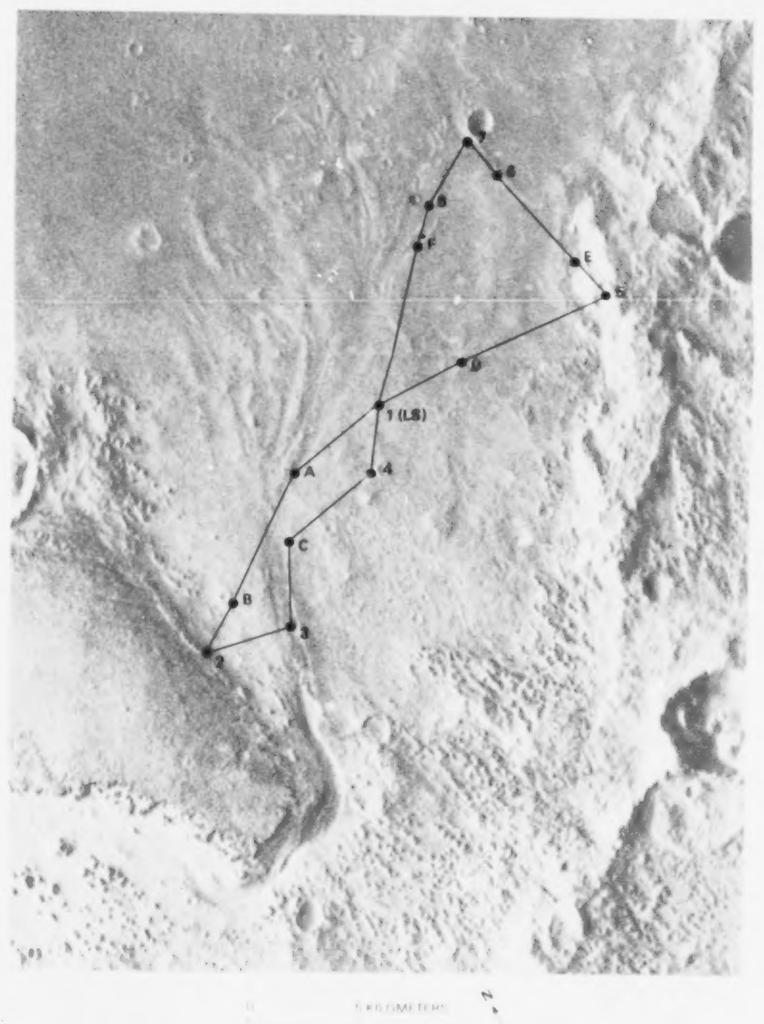


Figure 5. Proposed landing site (LS), rover traverses, and sample locations. Numbers mark primary sample locations; letters mark secondary target of opportunity sites. Samples and locations described in table 1.

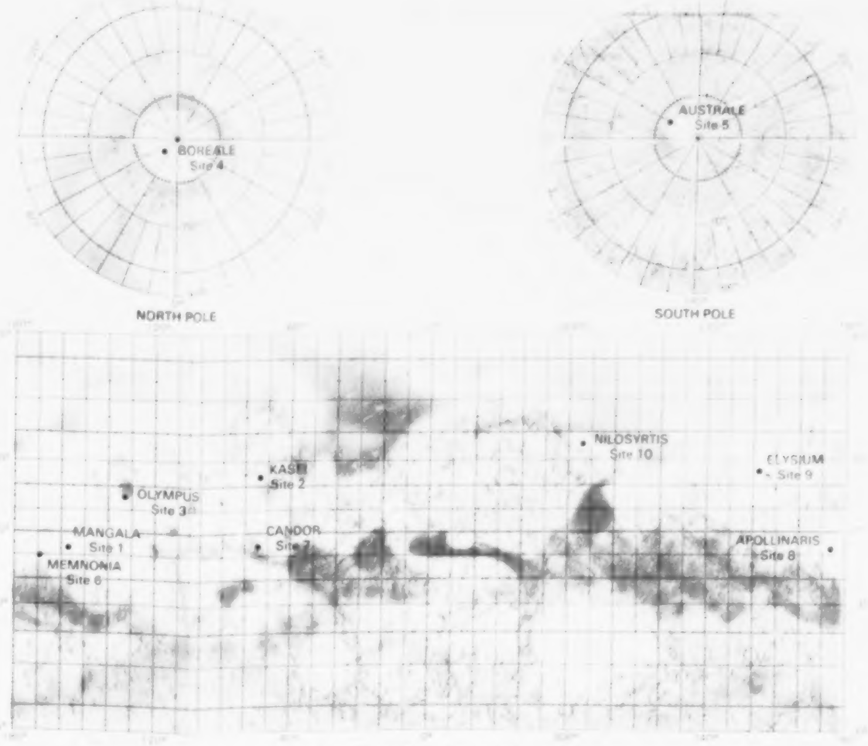


Figure 6. Planned science study areas on Mars that include candidate landing sites for future sample return missions.

MAP OF SCIENCE STUDY AREA 6, MEMNONIA REGION OF MARS

(MTM -10172)

By

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